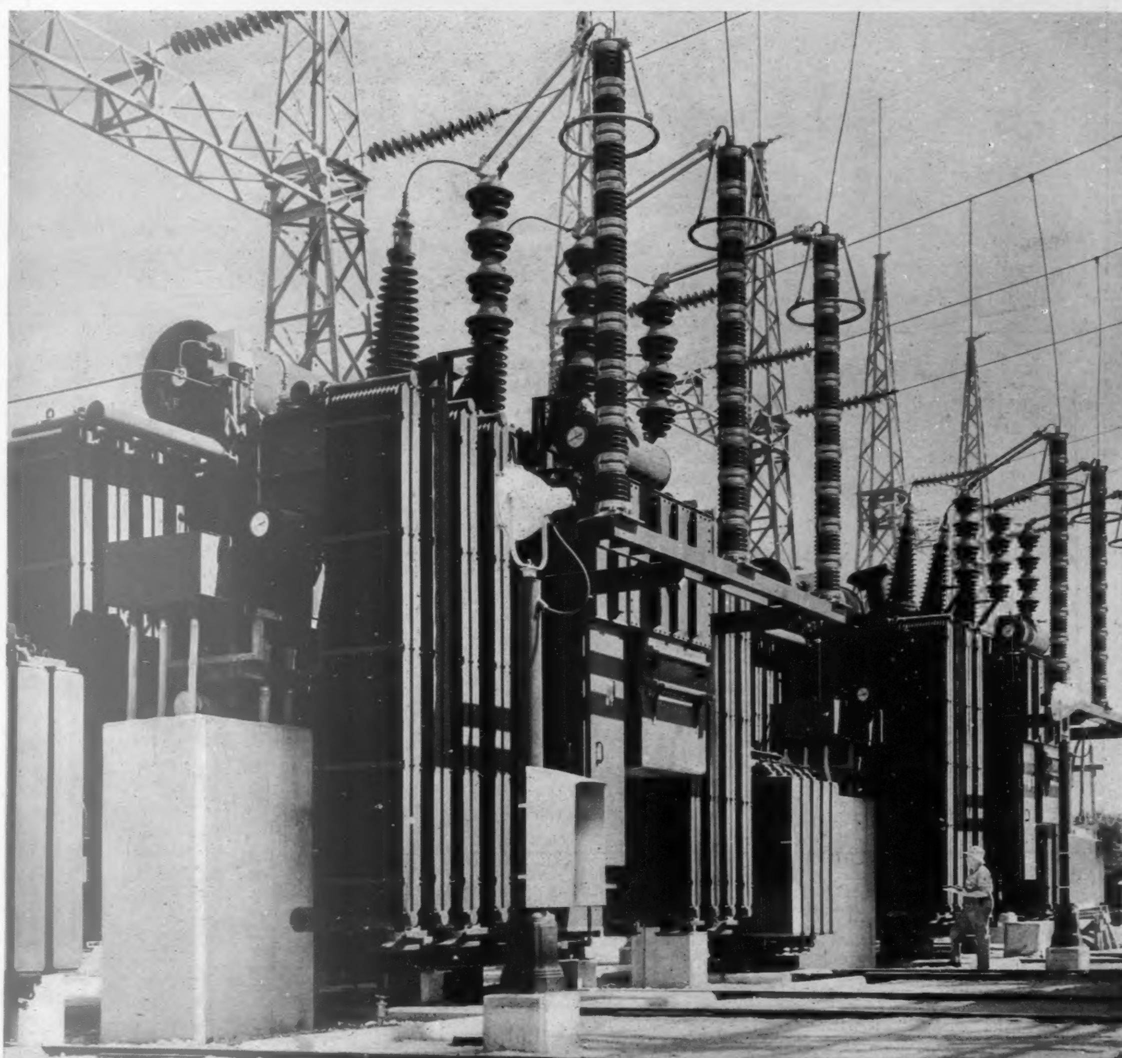
ALLIS-CHALMERS

Electrical Review



Third Quarter, 1948

NEW TRANSFORMERS for a recently completed station of a mid-west utility are in keeping with the power industry's efforts to meet sharply rising demands for power. These three-phase, 60-cycle units, rated 30,000/40,000/50,000 kva, are used to step up the generated voltage of 13.2 kv to transmission line voltage of 138 kv. The new distribution facilities constitute an important step in the company's current expansion program. Three similarly rated transformers will be installed at a future date.

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ALLIS-CHALMERS Electrical REVIEW

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Contents

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Emergency Sources *Boost*

Gasoline-driven induction motors help California to overcome acute power shortage.

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CONTINUED drought in the Pacific southwest, June floods in the Pacific northwest, and the early spring drought in central and northern California, leave much to be worked out in the way of prevention from similar future disasters. For drought, although not as spectacular as flood, explosions, or earthquakes, may create even greater disaster. And because a similar calamity could strike almost anywhere, a discussion of remedial measures developed to cope with the California situation may be of interest to all users and producers of power.

Wishful hoping for rain postpones full appreciation of impending disaster, and, in the meantime, dwindling precious water supplies are consumed or wasted. It takes time for regulatory bodies to put into effect emergency legislation and, unfortunately, these unavoidable delays cannot be synchronized with the demands of industry or agriculture. Unless the emergency is of prolonged duration, the usual time required for design, ordering, construction, and installation may preclude profitable use of all but stop-gap measures. For this reason, emphasis is given to the emergency power sources which successfully passed laboratory and demonstration tests and were in the process of construction at the time the emergency passed. They worked, and the experience gained should be helpful to engineers everywhere who someday may be faced with a similar problem.

Droughts breed unrest and fear

During such a calamity, the entire area suffers economic loss and discomfort, unemployment increases and a pall of insecurity, in some ways worse than that caused by war, descends upon the people. Such were the prospects for central and northern California in the early spring of 1948. The precipitation for 1946-1947 had been subnormal, reservoirs and ground water were low, rumors were prevalent that salt-water infiltration threatened several important pumping plants, and the 1948 rainy season was about over. The seriousness of the impending disaster is illustrated in Figure 1 showing the Salt Springs Reservoir of the Pacific Gas & Electric Company early in March, 1948. This was the general situation from the Tehachapi in the south to the Siskiyou mountains in the north.

Fortunately the rains did finally come. The drought-emergency, declared February 24, was pronounced over on April 12. Unseasonable April showers in the lowlands, and heavy snows in the mountains, brought forth assuring predictions that every major reservoir in the stricken area would be filled to overflowing.

Unfortunately, a progressive people tend to gear their expectations of nature's bounty to her average, and not to her minimum. Although California has had dry years before, conditions were greatly aggravated by an influx of population during the war, which has now become permanent, and to the inability to develop additional water and power sources due to wartime restrictions and reconversion delays.

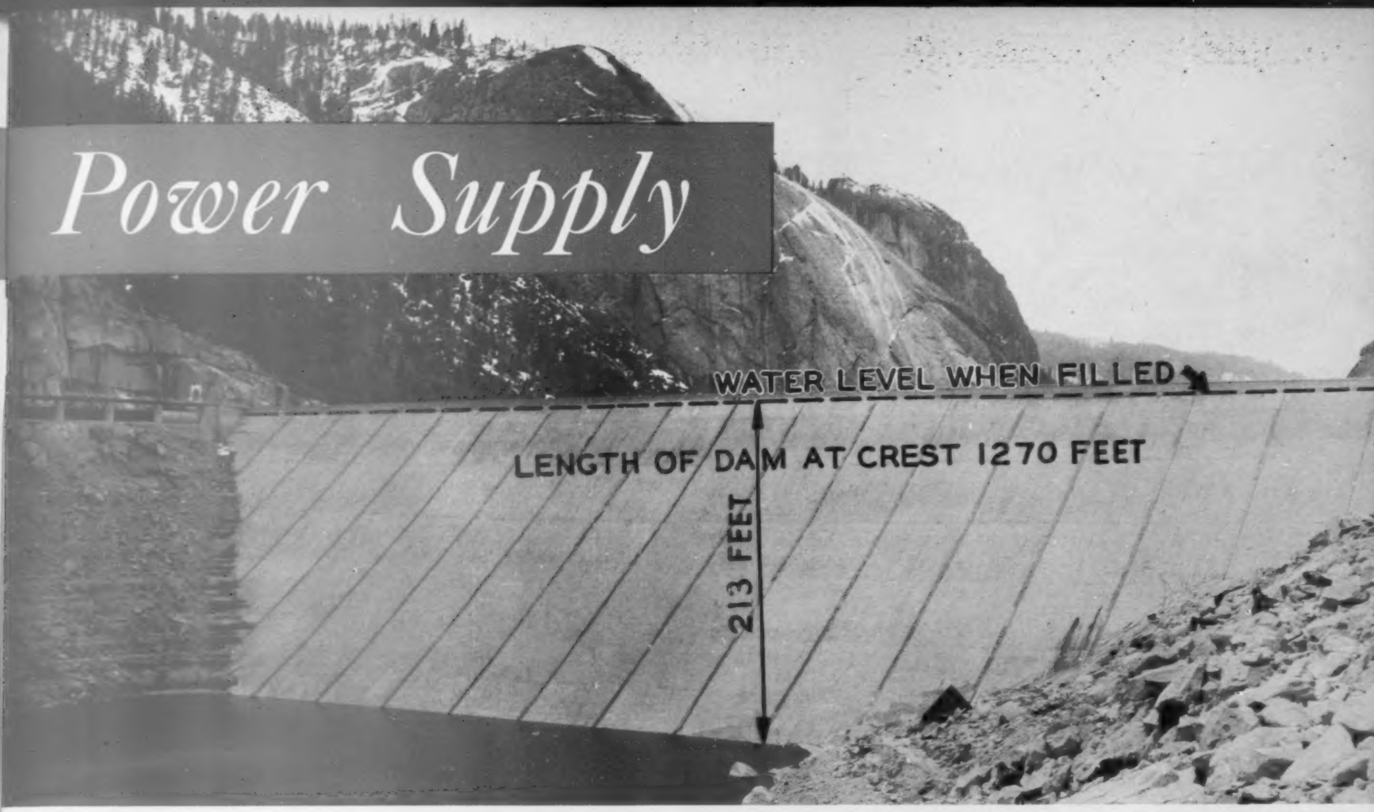
Drought may affect the electric power industry in several ways. Shortage of stored water seriously limits both potential hydroelectric kilowatts available as well as kilowatt hours; the shortage of energy being the most serious. Agricultural users turn from gravity water to pumping underground water, thereby greatly increasing the load on a system already short of energy to supply its normal demand. As the situation deteriorates, the increased scarcity of surface water and increased pumping lowers the water table and thus the pumping load tends to ever increase. The January and February pumping loads of the central valleys of California began to approach the value normally reached during the peak summer pumping season. Finally, as the supply of stored water reaches a critical point, authorities naturally regulate their release with chief regard given to domestic needs rather than to hydroelectric generation, thus adding to the seriousness of the power shortage.

During the California drought, regulatory bodies adopted various measures designed to aid conservation and equitable distribution of available resources. Local committees were formed to make recommendations on applications for new customers or additions to existing plants. Table 1, prepared by the California Public Utilities Commission under date of February 24, 1948, gives the estimated power savings for the various power conservation measures considered.

Emergency power needs careful study

Those considering supplementary power sources for a given emergency should carefully weigh the advantages and limitations of various stop-gap measures. Each of the several emergency power sources should be examined with reference to first cost, maintenance, and ultimate value. Since each of the emergency power sources has operating characteristics peculiar to itself, decision as to the most suitable for a given instance depends upon a careful analysis of not only the cost and operating characteristics of the source itself but upon the characteristics of the load to be supplied. Satisfactory operation of the entire installation must be primarily considered even above the imperative needs of prompt remedial action and the availability of certain equipment.

Power Supply



EXTENDED DROUGHTS breed fear and insecurity and disrupt the economic and industrial life of the afflicted area. This depleted water supply in the Pacific Gas & Electric Company's Salt Springs Reservoir on the Mokelumne River is a grim example of the disaster which threatened California during the early part of 1948. When this photograph was taken in mid-March, the reservoir contained only 6,500 acre feet of water compared to its capacity of 140,900 acre feet. Subnormal dryness reduced the water level 213 feet below the "full" mark, or 95.4 percent below normal. **(FIG. 1)**

Because of the many factors involved, it is highly probable that the best solution for one case may be undesirable for another. Requirements of agricultural, commercial, and industrial loads are different. Even within a given industry, individual differences in operating schedules, loads, or plant characteristics may be sufficient to indicate different solutions. Thus the following discussion is not intended to be an all-inclusive treatment of all possible power sources, but rather an outline of the salient features of several emergency measures.

Induction motors used as generators

The eminently satisfactory performance of induction motors in all phases of modern life has focused attention on them as the cheapest, most durable and fool-proof of all types of prime movers. Although not publicized, electrical utilities in special instances have, for years, operated induction motors as induction generators with equally satisfactory performance.

The availability of squirrel cage or wound rotor induction motors, together with the fact that the control equipment for induction motor operation will serve equally well for operation as an induction generator, are paramount in a period of power shortage. Fortunately, either type of motor will serve equally well as an induction generator; however, preference is given the squirrel cage motor because of its lower cost.

The practicability of the induction generator as an emergency power source was recognized early in the emergency. The University of California took an active part in acquainting industrialists and agricultural engineers in both technical and operational details. A small induction motor gasoline engine unit was mounted on a truck, and farm demonstrations were held throughout the stricken area. These demonstrations were very well received as a practical means of relieving the power shortage. This work was conducted by the Agricultural Extension Service through their county farm advisors, in cooperation with the Division of Agricultural Engineering and the Division of Electrical Engineering. During the first part of April, many firms advertised induction generator units already assembled. Figure 2 is a typical example.

TABLE 1

POSSIBLE SAVINGS IN PEAK DEMAND

	Estimate of Load at Generation Annual Basis	
	Kilowatts	Millions Kilowatt Hours
Reduction in frequency to 59½ cycles	45,000 to 60,000	205
Reduction in voltage of 5%	12,000 to 30,000	27
Daylight Saving, P. G. & E. evening peak	100,000 to 160,000	136
summer morning	0	0
Brown-out of display and sign lighting	90,000 to 100,000	75
Voluntary pledges	75,000 to 80,000	?
Curtailment	175,000 to 220,000	1,300

TABLE 2

OPERATING CHARACTERISTICS OF 3-PHASE WOUND ROTOR INDUCTION MOTORS

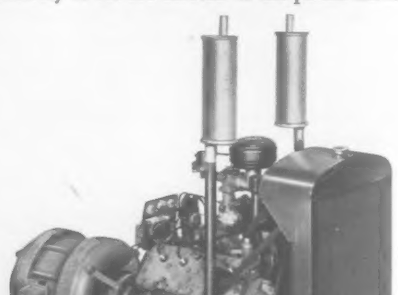
Nameplate Data Induction Motor			Experimental Values							
			Induction Motor				Induction Generator			
HP	Speed	Amps	Amps	Input KW	% Slip	% Speed	Amps	Output HP	% Slip	% Speed
15	720	44.0	44.0	12.6	8.9	91.1	44.0	15.1	7.2	107.2
15	1200	38.0	38.0	13.5	5.2	94.8	38.0	17.1	4.2	104.2
15	1200	38.0	38.0	11.4*	3.9	96.1	38.0	12.7	4.2	104.2
5	1200	?	25.0	3.9†	4.8	95.2	25.0	4.3	3.3	103.3

* Motor failed to develop nameplate output of 15 hp. Estimated shaft output 12.5 hp at 220 volts, 38.0 amperes and 1,150 rpm.
† Results from 5-hp, 110-volt induction motor at 3.16-hp output.

The basic principle of the induction generator is easily understood when one considers that the energy flow in induction machines is a reversible process. An induction motor energized from a power source develops mechanical power by running at a speed slightly less than its synchronous speed. Conversely, an induction motor driven in the same direction at a speed slightly greater than its synchronous speed will deliver electrical power when connected to a power system. If the machine is driven above synchronism by the same rpm that the machine normally operates below synchronism, the generator will deliver approximately rated current at rated voltage and rated efficiency, and the electric power output will be approximately equal to the rated shaft motor power. However, the generator power factor will be much lower than when operated as a motor.

Tests reveal safe loading data

Suppose a certain plant has a continuous load of 75 horsepower and the curtailment is 20 percent (i.e. power allotment equals 80 percent). A 15-horsepower, three-phase induction motor driven by a suitable prime mover such as a tractor or automobile engine, could supply the required curtailment and thus permit the plant to operate continuously at full load within rationing regulations. To accomplish these results, it is merely necessary to set the throttle of the prime mover so that



INTERNAL COMBUSTION engines were recommended by the University of California as practical power sources during the power emergency. Demonstrations were held on farms and in industrial plants of the stricken area to acquaint users with technical and operating details. (FIGURE 2)

the induction machine operates *above* no-load speed and delivers the full-load current given on the name plate of the machine.

Curves in Figures 3 and 4 were obtained on two 15-horsepower, three-phase 220-volt wound rotor induction motors during tests made in the electrical machinery laboratories at the University of California, Berkeley. The curves illustrate the significant electrical characteristics of the machines for both induction motor and induction generator operation. Significant results obtained from the curves, and from two additional machines, are given in Table 2. The tests on the 15-horsepower machines were performed with the terminal voltages held constant at 220 volts.

Although the practicability of operating induction motors as generators has been appreciated for many years, a survey of modern literature failed to disclose quantitative data sufficient to permit conclusions to be reached regarding maximum safe loading. For example, the circle diagram indicates that for the same stator current, the rotor currents during generator operation would be greater than during motor operation. Although the experimental results are in agreement with the circle diagram for stator currents at light loads, it was found that the rotor currents were equal for the same stator current for values of stator current near and slightly above rated. From this it is apparent that the copper losses in the machine (either wound rotor or squirrel cage types) should not exceed the values at full load for either motor or generator operation for stator currents up to and including full-load current.

For a given voltage, the core loss will be slightly greater for generator operation. However, if the resulting increased heat when operated as a generator is offset by better heat dissipation due to increased windage produced by the greater speed of the machine, the capacity of an induction machine would be slightly greater when operated as an induction generator.

The delivered output in kilowatts as a generator corresponding to a given stator current may be taken directly from the curves. The delivered horsepower output for the four machines, corresponding to full-load current, is given in Table 2. Attention is directed to the fact that each machine delivered an output greater than its name plate horsepower rating, or shaft output as an induction motor.

On the basis of the above it is concluded that squirrel cage and wound rotor induction motors should safely deliver a power output equal to, or slightly in excess of, their name plate rating when operated at rated voltage and full-load current as induction generators.

Induction generators are dependable

Although the induction motor is an inherently stable machine, attention should be directed toward possible difficulties of holding the load output constant. It is well known that mechanical prime movers require more or less constant supervision, and minor readjustments may be required from time to time, especially when using reconverted prime movers equipped with makeshift governing apparatus. However, induction generators should give a minimum difficulty from troubles of this kind because of their inherent stability and lack of tendency to hunt.

The inherent stability of the induction generator is apparent from the speed-output curves of Figures 3 and 4. In this case, the induction generator has a rising speed-load characteristic; i.e., an increase in power output requires an increase in speed. In contrast, most mechanical prime movers have a drooping speed-load characteristic, i.e., they slow down as the load is increased. Since operation occurs at the intersection of the two speed-load curves, it is apparent that conditions are inherently favorable for a high degree of stability.

In concluding the technical details of induction generator operation, it should be mentioned that a machine operated in this manner delivers kilowatts to the power system, while the power system supplies voltage regulation, frequency, and excitation. Since the power system supplies the excitation required to produce the rotating field, the induction machine is impotent unless connected to a power system. This is a decided advantage for temporary installations, as it provides an automatic safety feature. Except for very rapidly decaying transients, the induction generator supplies no current to a short circuit, and thus there is no danger of a back feed during short circuits on the utility system, or during switching operations.

During the operation of the induction generator, the power factor at the electric utility meter is lowered. In cases where billing is made on a power factor basis, the possibility of power factor penalties should not be overlooked. Of course, the increased reactive kilovolt-amperes may be compensated by any of the means ordinarily used to correct power factor, such as capacitors, over-excited synchronous motors, etc.*

The most serious disadvantage of the induction generator is its low power factor, however, power factor should be of minor importance in such an emergency. The major advantages are: availability of induction machines, low maintenance because of their rugged and fool-proof construction, inherent stability, freedom from hunting, no exciter required, no synchronizing required, low cost, few changes if any required in the rest of the electrical installation, and, after the emergency, potentialities for continued use in a vast multitude of applications in industry.

Any mechanically minded person should master the required operating techniques in a very short time. All that is required in placing the induction generator in service is to drive it at a speed somewhere between full-load speed as induction motor and full-load speed as induction generator and connect it to the power system. The throttle of the prime mover is then adjusted so that the machine operates *above* its no-load speed and supplies full-load current. From this point on the problem is one of maintaining a constant output by occasional readjustment of the throttle so that the machine delivers to the power system a load consistent with safe operating temperatures.

* Where these means are used to correct power factor, there is a possibility that dangerous overvoltages may be produced during switching operations, and technical analysis is indicated.

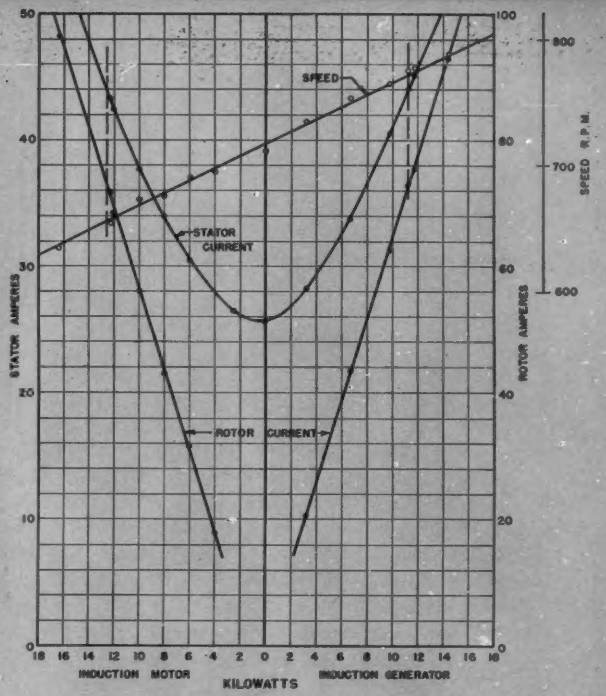


FIGURE 3

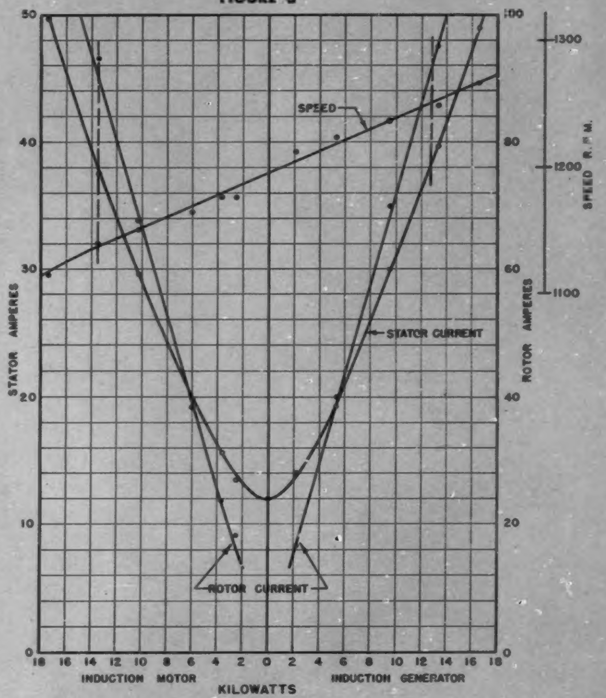


FIGURE 4

SPEED AND OUTPUT curves shown in the above charts are typical for three-phase, 220-volt wound rotor induction motors. Figure 3 shows the performance of a 720-rpm (synchronous speed), 44-amp motor, while curves in Figure 4 are for a 1,200-rpm (synchronous speed), 38-amp motor.

Mechanical drive merits consideration

Replacement of the electric motor with a mechanical prime

mover, although possibly a permanent solution, may involve prohibitive costs and untenable time delays. From an operating point of view, the most serious disadvantages of the mechanical prime mover are that it is limited to installations having a main drive shaft, and it must have a rating at least equal to the motor replaced.

A more satisfactory temporary solution would appear to couple the mechanical prime mover to the load with a clutch or a removable belt drive. During the major part of the time the prime mover would be uncoupled and the electric motor would drive the load up to the limit of its power allotment. The motor would then be disconnected and run idle during the time the mechanical prime mover was in operation. An advantage of this method is the flexibility in selecting convenient operating schedules, such as operating the mechanical prime mover at times when attendants are available. The convenience of such a dual drive should offset the small windage and friction losses of the induction motor running idle.

Installation of a supplementary mechanical drive, such as a pulley, on main drive shafts should present only a minor problem, and reports indicate that several such drives were improvised in the field by irrigation engineers. The structural modifications should not be difficult for small installations; however, the thrust of the belt is important where large capacities are involved.

Supplementary Mechanical Drive — Underdrive

To illustrate the use of a supplementary prime mover to underdrive a load, consider a 100-horsepower motor installation. An engine coupled to the motor shaft could supply a 20 percent curtailment or 20-horsepower, leaving for the electric motor a remainder of 80 horsepower.

The chief advantage of this scheme is that the prime mover need not be adjusted for a varying load. Any small amount of added power can be utilized, and therefore any prime mover can assist in relieving a power shortage. Obviously, the method can be used effectively with any type of alternating current motor, single-phase, three-phase, induction, or synchronous.

Supplementary Mechanical Drive — Overdrive

The overdriven case is similar to the preceding case in that the prime mover need not match a varying load. The method is particularly applicable for industrials where several motors are involved. By way of illustration, consider a load of six 50-horsepower motors, a 20 percent curtailment and a suitable prime mover. The connected load equals 300 horsepower, curtailment equals 60 horsepower, leaving an allowable load to be supplied by the electric utility of 240 horsepower. The prime mover adjusted to deliver 60 horsepower to one of the loads will supply 50 mechanical horsepower to the shaft load, leaving a balance of 10 electrical horsepower which will flow into the electric system, partially supplying the other motors. Thus by generating the required curtailment at some selected location, the plant may be operated continuously at 100 percent capacity within the assumed curtailment program.

Synchronous generator as power supply

Reports indicate that a considerable number of internal combustion engine alternator units were purchased by large electric power consumers for the emergency. These well designed units, installed by competent engineers, and maintained by skilled attendants, should give very satisfactory service. Theoretically, any synchronous machine powered by a suitable prime mover should give satisfactory performance as a synchronous generator. The difference between the operating characteristics of a synchronous motor and an alternator should be inconsequential as far as generator operation is concerned. For practical purposes, either machine should perform satisfactorily and selection might well be based on availability.

While either machine may be used as a generator, the converse may not be true — many alternators cannot be used satisfactorily as synchronous motors. Due to slight differences in the pole face windings, the starting winding of a synchronous motor may serve fairly well as a damping winding when the machine is driven as a generator; in contrast, the damping windings of some alternators may not develop sufficient torque to bring the machine up to speed when used as a motor. The future need for small synchronous generators would appear negligible in comparison to the potential demand for synchronous motors, and one might profitably consider the future value of the two types of machines.

The chief advantages of the synchronous generator are that it can supply both kilowatts and reactive kilovoltamperes. When over-excited the power factor at the electric utility meter is raised, and in cases where billing is made on a power factor basis, a bonus for high power factor should be an important consideration.

The most serious disadvantages of the synchronous generator are: high first cost; complexity of control apparatus, protection equipment, and instruments; necessity of generating both alternating current and direct current; high maintenance costs, and cost of skilled attendants. These disadvantages assume lesser importance as the size of the installation is increased.

In contrast to the induction generator, which must be connected to a power system, the synchronous generator may be operated in synchronism with the power system, or it may be operated as an isolated plant. In many cases it was advantageous to divide the load so that part was supplied by the utility, and the remainder by the synchronous generator operating as an isolated system.

The characteristics of the load are the most important factor affecting the successful operation of the small isolated system. Heating and centrifugal pump motor loads should be the simplest to serve. Lighting and timing devices inherently possess more exacting requirements. Large motor loads during starting may cause objectionable voltage and frequency variations and instability especially loads such as rock crushers, rolls, mills, compressors without unloading valves, etc.

In contrast to the induction generator, the speed-load curve of the synchronous generator at constant frequency is a straight line, and, as a consequence, the control of output when operated in synchronism with a large power system is more difficult. Synchronous machines are very sensitive to system disturbances, and voltage disturbances originating at distant points on the utility system may produce violent transients and result in out-of-step operation. These complications are such that it is highly probable that operation of synchronous generators in synchronism with a power system is beyond the ability of those not especially trained in power plant operation. Installations designed for isolated plant operation should not be operated in synchronism with a large power system prior to investigating the short circuit interrupting duty imposed on the circuit breakers.

Choose your control power source

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Space, location and operating needs influence selection of control power source.

PERSONNEL experienced in the application of metal-clad switchgear generally can choose the proper source of control power without giving the matter a great deal of consideration. However, the engineer who only occasionally faces the problem of writing specifications for new installations of metal-clad switchgear sometimes does not realize the importance of such a choice.

Choice depends on needs

Selection of the proper control power source rests upon these three important factors:

(a) Reliability of operation

(b) Maintenance required

(c) Effect on cost of equipment and installation

Reliability of the control power source is the most important factor to be reckoned. Since the bulk of the expense in a switchgear installation is involved in the fault protective equipment, it is mandatory that this protection be available at all times. A single failure in the tripping source on a switchgear line-up could cause considerable damage if, for example, a circuit breaker does not operate to isolate a faulted circuit. Or, the loss of control power preventing the automatic reclosing of a circuit breaker after a temporary fault may cause a prolonged outage. It is essential, therefore, that a reliable source of control power should be chosen. This requirement is more important in some applications than in others.

Thought should be given to the degree of maintenance, which is involved. A control battery source may be suitable in a station where servicing personnel is always at hand. In remotely located stations it may not be feasible to arrange such frequent service visits as the proper maintenance of the battery would require. Where limited skilled labor is available, it is important to make the control scheme as simple as possible.

The cost of the switchgear as affected by the various control sources is another important factor to consider. In many cases where there is no particular technical advantage of one source over another, a substantial saving in the cost of the switchgear can be obtained by choosing the least expensive scheme. The economics involved are analyzed in Figures 7 and 8.

Common control sources available

Choosing proper control sources depends upon the type of installation. In most applications where large groups of switchgear are installed, the most commonly used is the single d-c control battery for both tripping and closing circuit breakers. Central stations, large indoor substations, and groups of primary switchgear in industrial plants almost invariably use a station battery of substantial capacity. These batteries are usually rated 125 volts. Sometimes, however, 250-volt units are found where the amount of control power required is rather large. Ratings of the control batteries are determined by the closing and tripping currents of the circuit breakers, the number of indicating lamps or other continuous loads drawn from the battery, and the amount, if any, of emergency lighting which the battery will be required to furnish for a given period of time.

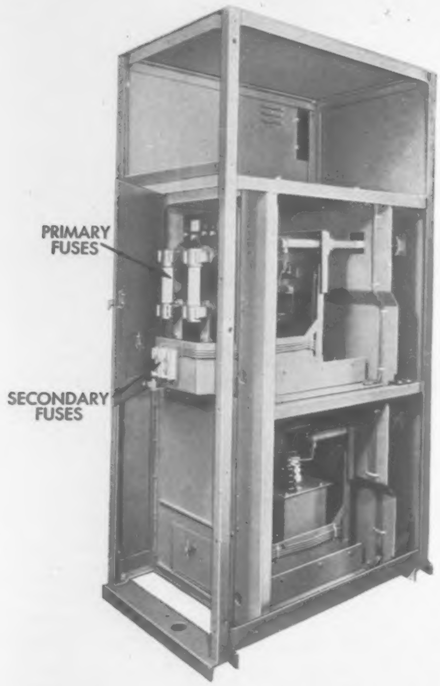
In the usual installation of metal-clad switchgear, if no emergency lighting load from the battery is required, a battery with an ampere rating for one minute down to 1.75 volts per cell equal to the closing current of the largest circuit breaker service is usually sufficient. Useful information for determining more accurately the battery ampere rating can be found in two articles published in recent years.*

These batteries are generally furnished with two or three step-battery racks, and are normally mounted in a separate

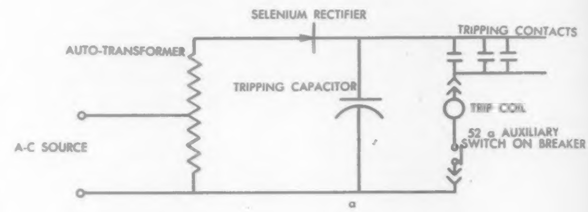
* 1. ALLIS-CHALMERS ELECTRICAL REVIEW, December, 1944, issue, "How to Select Storage Batteries for Switchgear," by Robert Loewe.

2. *A.I.E.E. Transactions*, Vol. 66, 1947, "The Application of Storage Batteries to the Control of Switchgear," by E. A. Hoxie.

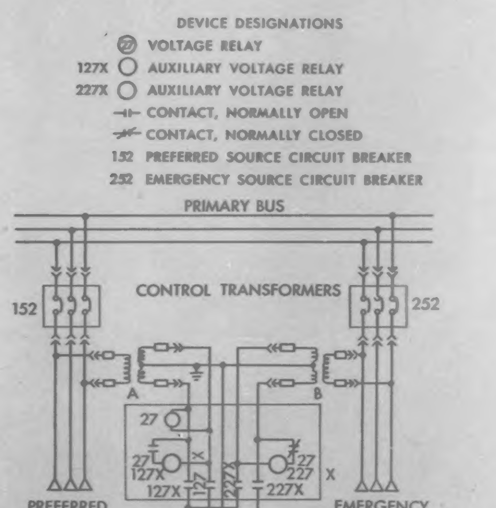
CONTROL BATTERIES for indoor stations are mounted in banks separate from the switchgear. This 60-cell bank provides 125-volt closing power for 15-kv circuit breakers in a grain and malt plant. **(FIGURE 1)**



CONTROL TRANSFORMERS built into the metal-clad switchgear line-up are another widely used source of control power, especially where limited housing is inadequate to accommodate batteries. Transformer and fuses can be easily withdrawn for either maintenance or inspection. (**FIGURE 2**)



CAPACITOR TRIPPING DEVICES, like the one diagrammed and illustrated here, store energy for tripping purposes. Although the primary voltage may drop due to the occurrence of a fault, the capacitor insures adequate power to operate the trip coil. (**FIGURE 4**)



AUTOMATIC TRANSFER SCHEME of control circuit between two control power transformers is necessary when two incoming main power lines feed switchgear. A selector switch can be added to permit choice of preferred power source. (**FIGURE 3**)

location external to the switchgear. They can be charged with static type battery chargers of either the self-regulating or manual rheostat-controlled type. For higher ampere charging requirements, the use of a small motor generator set may be desirable. The use of station batteries rated less than 125 volts is not recommended ordinarily because of the high currents necessary to furnish sufficient power to the circuit breaker closing coils. Also, special circuit breaker closing coils for these lower voltages may not be readily available.

Two grades of battery cells are commonly employed. These are the pasted plate type and the Planté type. The Planté cell is rated for longer life expectancy and is more expensive for the same ampere hour capacity. A typical 60-cell control battery installation is shown in Figure 1.

Transformers need less space, maintenance

Another widely used form of control power is the control power transformer. Quite often it is employed where a 125-volt control battery requires too much housing space or the maintenance requirements are such that a battery is not desirable. By connecting the primary of this transformer directly to the source of power as it enters the switchgear we are assured of a reliable source of a-c control power. The secondary of this transformer is connected to a static type rectifier, the d-c output of which is applied to the circuit breaker closing coil for closing energy. Figure 2 shows the manner in which this control power transformer is mounted in the metal-clad switchgear lineup.

Each circuit breaker in the lineup must be supplied with its own rectifier when an a-c solenoid rectifier closing scheme is used. Ordinarily only one control power transformer of suitable size is required for each complete metal-clad switchgear lineup. In cases where there are more than one incoming main power source to the switchgear it is usually necessary to apply one control power transformer connected to each source. With this arrangement control power is available even though one or more of the sources may not be energized. Some type of automatic transfer switch must be installed to transfer the secondary circuits from one control power transformer to the other. A scheme of this type involving two incoming lines is illustrated in Figure 3.

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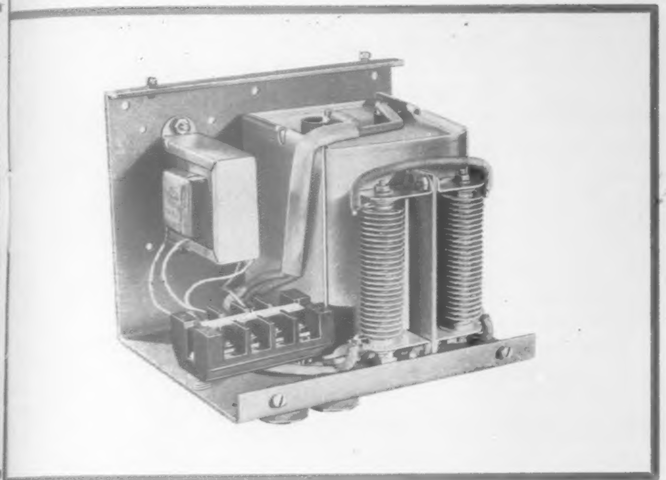


Transformers supply tripping power

The secondary of a control power transformer is also used as a source of supply for tripping power. If this source is connected directly to an a-c shunt trip coil, proper tripping operation cannot be assured under all conditions since the primary voltage may drop appreciably and leave insufficient voltage to operate the trip coil. A capacitor type tripping device is often used to overcome this deficiency.

A small rectifier in the device maintains a charged capacitor which is discharged through the d-c shunt trip coil when tripping is desired. The capacitor remains charged with sufficient energy to operate the trip coil even though the primary source of power may have dropped upon occurrence of a fault. A simplified schematic diagram of the capacitor trip device is shown in Figure 4.

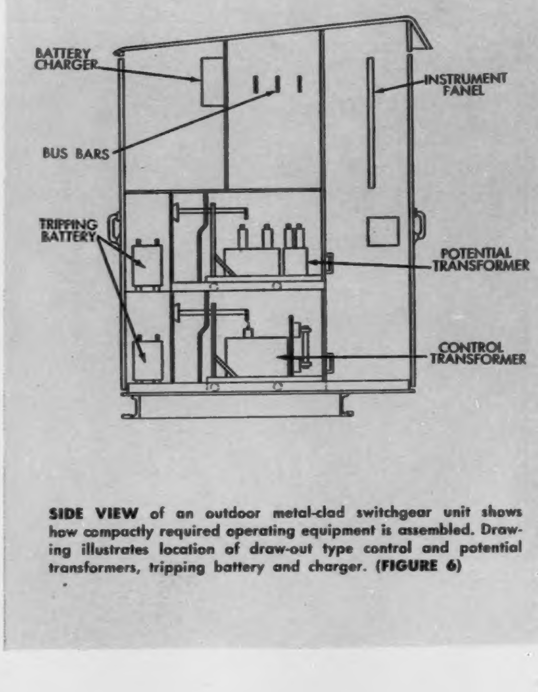
This control power transformer is also used to supply power for indicating lamps. It can be used also for other low current a-c circuits, such as small lighting circuits or single phase convenience outlets. Average installations of switchgear require a single-phase transformer of approximately 5 kva, mounted with its fuses on a drawout type carriage in the switchgear. For larger circuit breakers, or where separate a-c circuits draw more current, 10, 15, or 25-kva transformers may be required. Some of the larger transformers are mounted stationary in a switchgear auxiliary unit. Generally, it is desirable to provide drawout or disconnecting type fuses so that the transformer and fuses may be safely isolated from high voltage circuits for inspection or maintenance.

Separate a-c source has shortcomings

Using an a-c source of control power, which is independent of the primary bus of the switchgear, has inherent disadvantages. It is seldom recommended for the source of tripping power since voltage may be lost on the independent circuit, thereby preventing the switchgear from effecting any tripping operation until control voltage is restored.

Where a separate a-c source is used for circuit breaker closing power only, circuit breakers can be closed, though this is not recommended, with a manual operating handle generally provided for maintenance purposes. This expedient, however,

D-C TRIPPING BATTERIES are an economical source of power for installations where switchgear is located outdoors or where station batteries are not feasible. Rated either 24 or 48 volts, batteries reduce switchgear costs considerably by eliminating need for tripping capacitors. **(FIGURE 5)**



SIDE VIEW of an outdoor metal-clad switchgear unit shows how compactly required operating equipment is assembled. Drawing illustrates location of draw-out type control and potential transformers, tripping battery and charger. **(FIGURE 6)**

cannot be used for 5-kv to 15-kv air circuit breakers since they should be closed quickly to prevent excessive burning of the contacts. A separate a-c source should, therefore, not be used for closing power to circuit breakers if operating conditions require immediate or reliable electrical closing operations.

D-C tripping battery cuts cost

In installations where the source of control power must be housed in the switchgear lineup, the use of a 125-volt d-c control battery requires too much space to be housed economically. Generally, this situation arises where outdoor switchgear is concerned. However, it may be desirable to use a battery source for tripping power. Where this condition exists, a control power transformer furnishes the closing power, using a small 24-volt (Figure 5) or 48-volt battery, with trickle charger, as the tripping source.

The tripping battery and control power transformer are housed in the metal-clad switchgear lineup (Figure 6). Since the use of the tripping battery eliminates the need of furnishing a capacitor tripping device for each circuit breaker, a substantial reduction in the cost of the switchgear is effected if approximately four or more circuit breakers are included in the lineup.

General application of power sources

For large groups of indoor metal-clad switchgear where approximately four or more circuit breaker units are involved and battery maintenance does not present a problem, a 125-volt station battery is generally the most inexpensive and practical means of solving the control power problem. Space must be available for locating this station battery in the building in which the switchgear is located.

For small groups of indoor and outdoor switchgear it is advisable to use control power transformers for the closing source, with either a tripping battery or an a-c capacitor device for tripping. A reliable d-c source may be used in all cases, if it is nearby and already available.

For large groups of outdoor switchgear, it is most economical to use a control power transformer for closing and a small tripping battery for tripping. Capacitor type trip devices may be used in instances where maintenance requirements render batteries impractical.

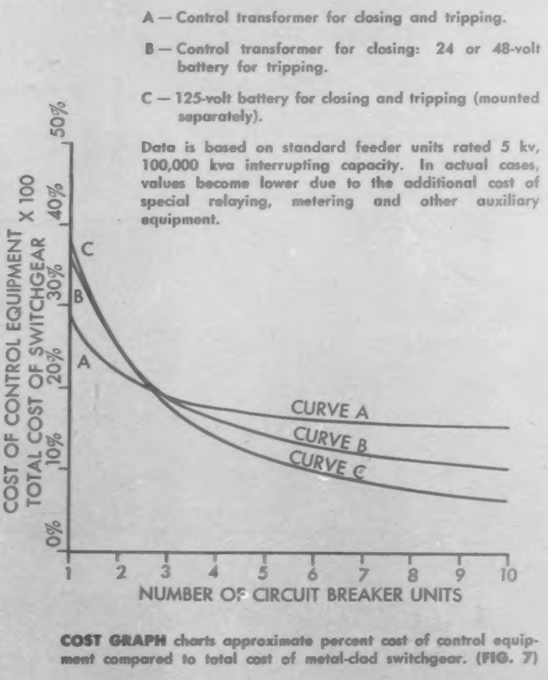
Since most low voltage air circuit breakers are manually operated with series type tripping devices, no control power source is required. Suitable rectifiers are furnished where electrically operated circuit breakers are included. Rectifiers are fed directly from the a-c bus, or through small control power transformers. Tripping, under other than fault conditions, is accomplished by a manual trip button. However, where remote electrical trip is desired, a-c trip can be used. A control battery which is already available can be used readily as a control power source.

Type of source determines cost

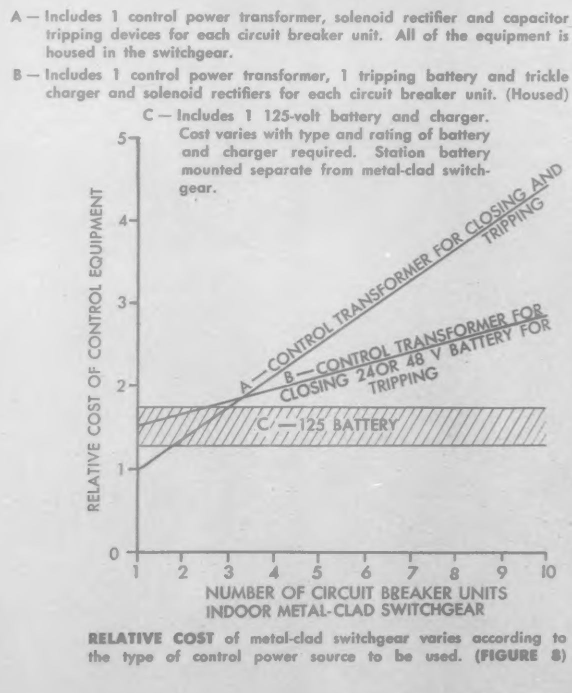
The cost of metal-clad switchgear varies with the type of control power source. For installations of single switchgear units, the control power source and allied equipment accounts for 30 to 40 percent of the total cost. Figures 7 and 8 show that a 125-volt battery is more expensive than other means when only a few circuit breakers are controlled. In addition, space must be provided for locating this battery outside the switchgear. As the number of units increases, the 125-volt control battery becomes most economical.

These considerations cover only the most common applications where electrically operated circuit breakers are involved. Very few, if any, modern installations of metal-clad switchgear with power circuit breakers now employ manually operated circuit breakers. Although there are also many circuit breaker tripping schemes[1] applicable where no control power source is required, the large majority of switchgear installations utilize control power sources outlined in the foregoing paragraphs.

[1] "Methods of Closing and Tripping Circuit Breakers," R. B. Steiner and Robert Loewe, ALLIS-CHALMERS ELECTRICAL REVIEW, Fourth Quarter, 1946.



COST GRAPH charts approximate percent cost of control equipment compared to total cost of metal-clad switchgear. (FIG. 7)



RELATIVE COST of metal-clad switchgear varies according to the type of control power source to be used. (FIGURE 8)

POWER for modern Chemical Plants

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Distribution equipment selected to meet industry's big and frequently changing loads.

THE CHEMICAL industry is the largest consumer of electric power among major industries. In 1945, this industry consumed 20 percent of the total kilowatt hours used by the major industries. Between 1939 and 1945, the electrical demand of the chemical industry grew from 1,900,640 to 4,680,621 kilowatts. Consumption increased more than three-fold to over 29.5 billion kilowatt hours. This energy was consumed at a load factor better than 70 percent due to the continuous processes typical of the chemical industry.

To use this enormous amount of power, the chemical industry draws on the electrical industry for the full range of electrical equipment, ranging from turbo-generator sets to electronic control devices. Economic selection and use of electrical equipment in a chemical plant is complicated by the fact that the chemical industry is subject to rapid changes in process requirements and high obsolescence. The design of the chemical plant's electric facilities should meet the challenge of frequent changes in load distribution and growth. The need for reliable power supply is indicated by the high load factor for the industry.

An electrical distribution system based on these facts should satisfy the conditions of ample capacity, flexibility and reliable supply.

The distribution of power starts at the secondary of the primary substation or the power house feeder switchboard. The substation is normally located in an accessible area as close to the center of load of the plant as is convenient. The location is determined after consideration of such factors as the effect of fumes, corrosive vapors and fly-ash on insulators, switches, and transformer enclosures.

Load determines size of equipment

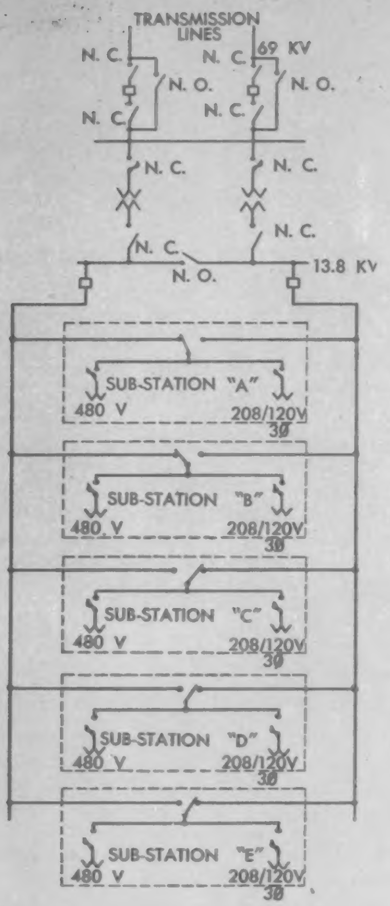
In planning the size of the primary substation, the kind of products likely to be manufactured will indicate the size and nature of the load to be supplied. An ammonia plant of given tonnage output would require many times the electric power consumed in a sulphuric acid plant of the same capacity. An analysis of the type of process which could conceivably be installed at the plant site will establish whether the ultimate plant load will be in the neighborhood of 1,000, 10,000, or 100,000 kilowatts.

Normally a single primary transformer sized to take the entire plant load makes the most economical installation. However, it is desirable to have more than one unit when the connected load is large.

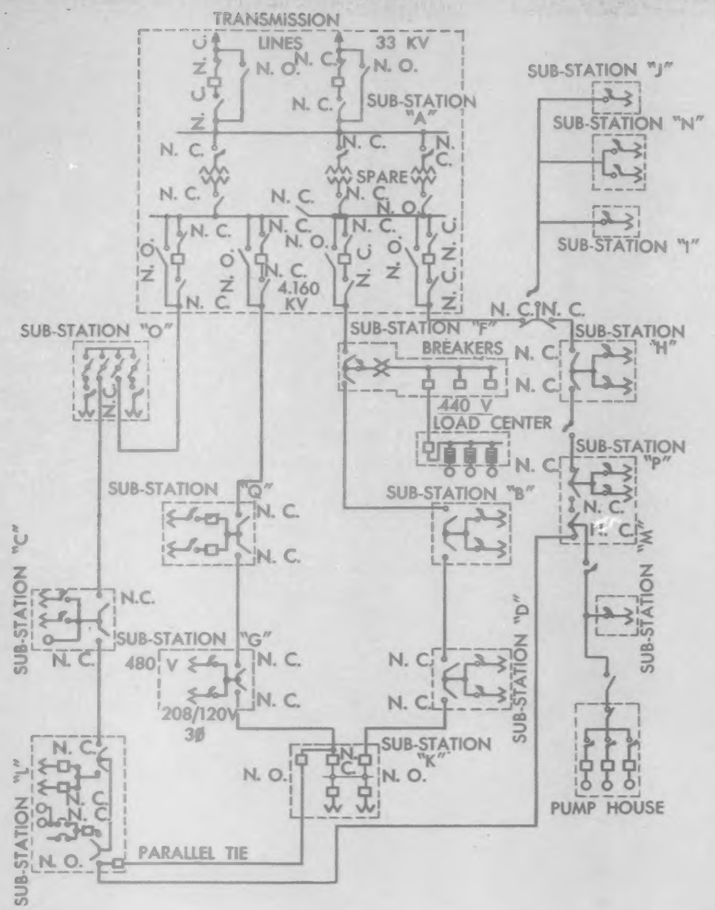
The continuous nature of most chemical processes makes installation of a spare transformer a necessity. Cost of the spare unit is reduced in inverse proportion to the number of primary transformers supplying the load. The number of units selected is an economic compromise between the installed cost of the spare versus cost of additional site, extra transformer and switching for more than one unit. The spare need only be rated at 75 percent of the operating transformer, provided it has provision for external forced cooling.

The establishment of the probable ultimate plant load insures that a proper selection of interrupting capacity for secondary circuit breakers will be made. Too often the interrupting capacity of feeder and distribution breakers is a limiting factor on plant electrical growth, with subsequent expenditures for replacement and rehabilitation.

UNIT SUBSTATION LAYOUT provides versatility in this corn products refinery installation in the mid-west. High voltage 150,000-kva switchgear and metering equipment feeds a 4,160/480-volt, 500-kva Chlorextol liquid filled transformer and six low voltage circuit breakers.



TYPICAL DUAL FEEDER distribution system for 13.8 plant voltage. Provides double protection where reasonable outage time is tolerated. (FIG. 1)



LOOP FEEDER distribution systems, like the one diagrammed above, provide adequate shutdown protection. (FIGURE 2)

Unit substations recommended

With the primary transformer size fixed, the system can be built up to the capacities of the transformers. Further expansions can be accommodated by duplicating the basic system and providing for emergency ties among the spare transformers with interlocked switching arranged to limit the number of transformers, paralleled at any one time, to the interrupting capacities of the distribution system. This concept of unit systems can be applied to the installation of secondary transformers, distribution lines and load centers, as will develop later.

The unit type substation is gaining popularity in the chemical industry. Advantages of having the primary and secondary switching closely integrated with the transformer and housed against weather, fumes, corrosive vapors, and dust are evident. Repetitive manufacture, and high installation labor costs are offsetting factors which are narrowing cost differentials between conventional transformer substations and the unit type.

Within the plant, the secondary feeder system distributes power to the loads at voltages that range from 13,200 volts to 240 volts. Probably the most frequently used distribution voltage is 2,400/4,160 volt wye. It has been found economical to limit feeder capacities to a maximum of 600 amperes. If the number of such feeders becomes unwieldy the distribution voltage should be increased. Our recent studies have indicated the following voltage classifications as yielding optimum distribution efficiencies with minimum number of feeders.

For plant capacities to	5,000 kw	2,400 delta or 4,160 Y distributions.
" " " "	15,000 kw	6,900 volt
" " " above	15,000 kw	13,200 volt

These voltages are based on feeder lengths up to a mile for three-conductor cable or the equivalent length in overhead spaced conductors giving the same voltage drop at full load.

These classifications, of course, are modified by unusually long transmission distances. In the case of a powder plant where manufacturing buildings are spread out over long distances, it may be necessary to go to higher voltage than those indicated, for voltage regulation reasons.

The mode of distribution in most chemical plants is overhead with an increasing trend toward underground installa-

tions. Although the cost of underground distribution is several times that of overhead construction, where conditions are favorable the advantages of underground distribution in a chemical plant are many. Chief among these are freedom from lightning outages, flashovers, ice, and wind hazards. The chief disadvantage, other than cost, is the relative inflexibility of the underground system.

Alternate feeders forestall shutdown

With most chemical plants operating 24 hours a day, any lengthy interruption of service can be costly in loss of production. In some types of continuous processes, even a brief shutdown can prove quite costly. For such plants alternate feeders to secondary transformer stations are imperative.

Two commonly used systems providing alternate feeders to important loads are the dual feeder system and the loop feeder system. In the dual system two feeders, each originating at separate primary transformers are paralleled to each secondary transformer. Only one feeder serves the load; the other being connected manually or automatically by means of throw-over switches on primary transformer or feeder failure. In the loop system, the secondary transformers are arranged in series on two feeders originating at two separate transformers. When connected at their ends the feeders form a loop.

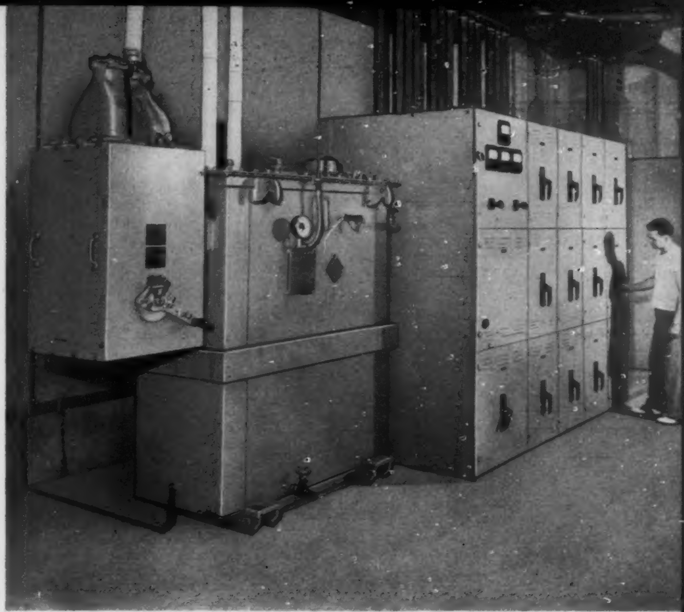
In both of these systems, switching time for selecting alternate feeders, although relatively short, could not be tolerated in some processes which must run uninterruptedly. To serve such processes the spot network is frequently employed, wherein the load is connected to two or more secondary transformers through suitable automatic switches. The number of network installations is still quite small. The cost of this system can be justified only where power interruptions could cause loss of production exceeding the differential cost between this and the other two systems.

Figure 1 illustrates the dual feeder system schematically. The throw-over switches shown are load-break oil switches. They are located in the secondary substation and are readily accessible to plant maintenance forces. Where reasonable outage time can be tolerated, this system is the most economical for the duplicate protection afforded.

Motors influence transformer size

The loop feeder system is illustrated in Figure 2. It is normally operated as two separate feeders. On feeder outage, sectionalizing switches can quickly be opened to isolate the faulted section of cable and operation can be continued on the remaining feeder. Each feeder is sized to carry the load normally carried by both feeders at a voltage regulation sufficient to keep motors operating within their over-current trip ratings. This is justified since operation in this fashion is unusual and not of frequent occurrence. At such times, full operation at poor voltage regulation is accepted as an alternative to partial loss of production.

The duplicate feeder is not usually carried beyond the secondary transformer. The reliability of transformers has increased over the years to a point where chances of failure in



BASEMENT INSTALLATION of a unit substation may be practical where floor space is at a premium. Because several large load-center substations were installed in a small room, transformers were water cooled.

a properly loaded transformer are remote. In plants where there are enough secondary transformer stations to justify the expense, a complete spare transformer of a rating equal to 75 percent of the largest operating unit on the plant site is carried on a portable truck.

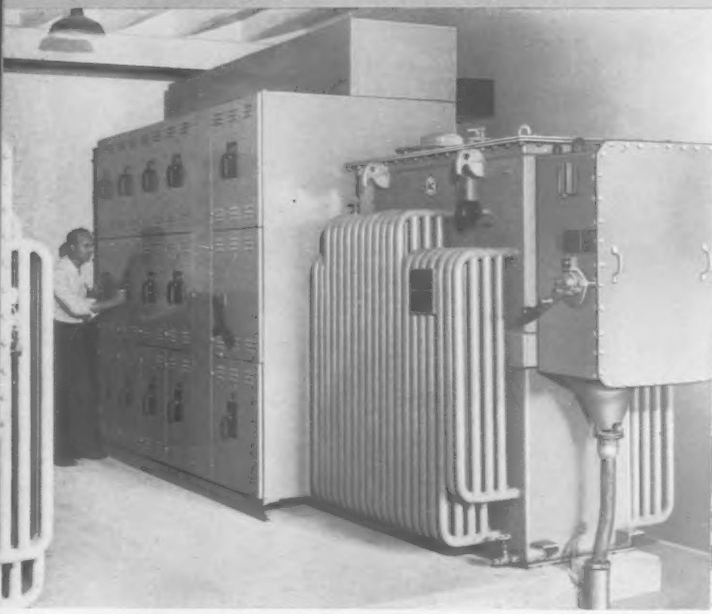
The secondary transformer is located close to the center of load in a building or plant load area. The sizing of the unit will depend largely on the proximity of the load to be served by the transformer, without exceeding reasonable voltage drops and power loss in the secondary cable runs.

The secondary transformer utilization voltage for power has been generally standardized at 440, three-phase. Experience has taught that motors up to approximately 125 horsepower can be economically installed and operated at 440 volts. It is generally more economical to go to some higher voltage such as 2,200 volts for all motors above approximately 125 horsepower. In such cases, larger motors can be operated at the distribution voltage, obviating the need for secondary transformation.

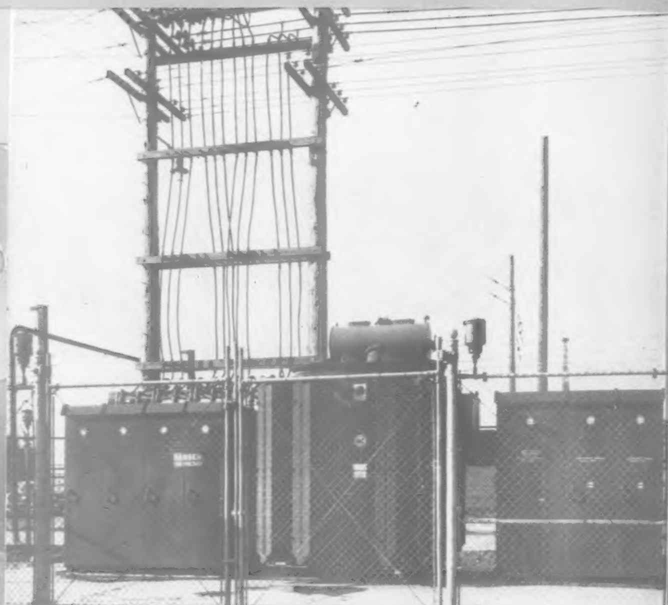
By limiting the size of motors operating at the lower power voltage it is possible to choose a secondary transformer size which can serve most load aggregations economically. Experience has shown that two standard sizes can meet more than half the chemical load requirements conveniently. These are the 300- and 500-kva, three-phase transformers.

Economy favors three-phase transformers

In the preceding discussion the use of three-phase transformers has been implied. The trend in the chemical industry is away from the use of three single-phase power transformer banks. The old argument that a bank of three single-phase transformers can be operated in open delta on failure of one unit does not overcome the desirable features of the three-phase transformer. It is not always possible to carry the load



FIFTEEN LOW VOLTAGE BREAKERS are incorporated in this load-center unit substation. Transformer is Chlorextol liquid filled, eliminating fire hazard. Only a narrow space is needed behind substation for inspection.



OUTDOOR MULTI-CIRCUIT unit substations are often used in the petroleum and chemical industries. This 5,000-kva, 13,200/2,400-volt unit has roof-mounted low voltage bushings. Feeder units are throat connected.

continuously on a bank in open delta, particularly if the bank was loaded near capacity prior to the loss of one unit. A spare three-phase mobile transformer can be installed temporarily in about the same time it would take to remove one transformer from a single-phase bank and reconnect in open delta.

The three single-phase units do not lend themselves very well to enclosure for operating in adverse atmospheres. Space in many cases is another important consideration in favor of the three-phase transformer. In this respect the unit type substation complete with primary and secondary switches in suitable enclosures has met an important requirement in some chemical plant distribution systems. (See illustration.)

Standardization of transformer at some such rating as 500 kva has the advantage of limiting the size and cost of secondary feeder breakers. It makes it possible to load a transformer most efficiently without having to extend secondary feeders long distances to acquire the necessary load, with resultant savings in copper cost and improved regulation.

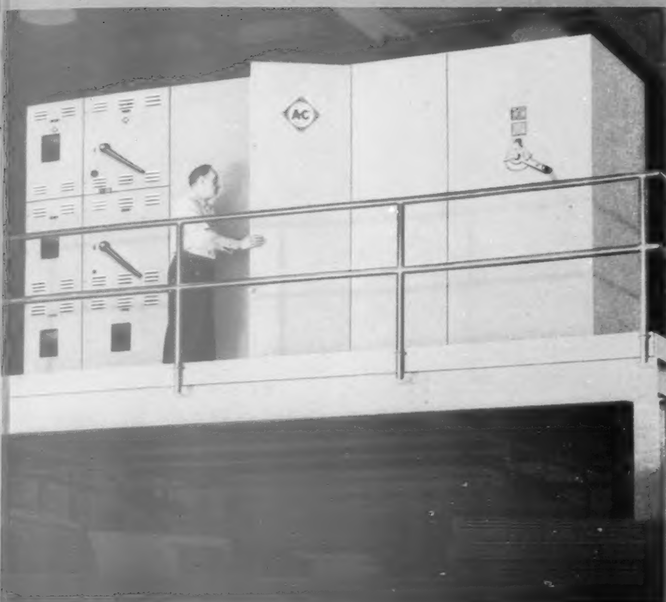
Unit subs aid expansion

Standardization of transformer capacity permits the expansion of the electrical distribution system to proceed in a succession of unit blocks. Unit substations of standard ratings can be added at convenient locations up to the capacity of the distribution feeders. It will be remembered that these feeders were sized to handle the primary transformer capacity. If it becomes necessary to go beyond this point a new primary transformer is added, and further growth is by similar unit blocks. In practice, the system works economically since no major investment need be made for future expansion until needed.

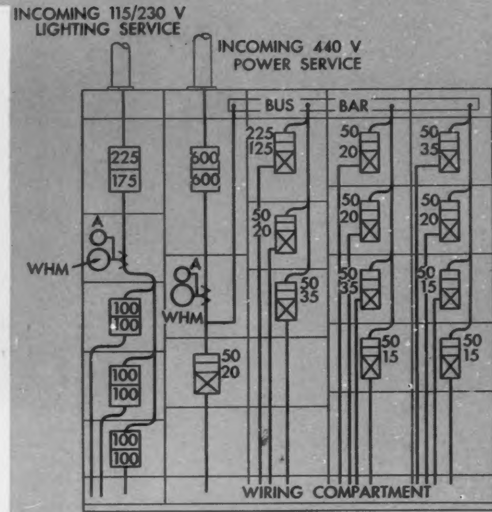
At the time the unit substation is purchased, space is provided in the switch compartment to house a predetermined number of feeder switches, all of which need not be purchased initially. To carry the concept of expansion in unit power blocks to another logical step, all feeder sizes are rated alike. It has been found that 400- or 600-ampere feeder switches are convenient sizes for a 500-kva transformer.

Each secondary feeder breaker protects a secondary feeder cable which terminates in a load center consisting of a group of switches and starters. Because of corrosion and explosion hazards, in chemical plants it is becoming common practice to place these load centers in individual cells in areas of the plant free of fumes, vapors and dust. Such procedure permits the use of standard enclosures for the secondary switches. All controls are located in non-hazardous areas where they can be readily serviced by plant maintenance forces with minimum risk. New load centers are added to the standard feeder until the capacity of the feeder is reached. Additional feeders are added as needed until the capacity of the substation is reached.

Figure 3 shows the arrangement of a typical prefabricated load center. This load center includes a metering compartment

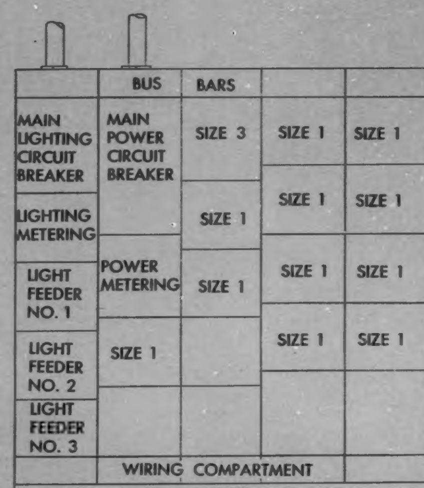


BALCONY MOUNTING of unit substations, like this 500-kva unit, keeps them safe from water under pressure used for washing down processing equipment, yet near enough for quick operation when necessary.



(a)

PREFABRICATED LOAD CENTERS are built to comply with safety, economy and minimum space requirements. Diagram (a) illustrates a typical secondary load center wiring arrangement, while (b) shows compartment lay-out. **(FIGURES 3a and 3b)**

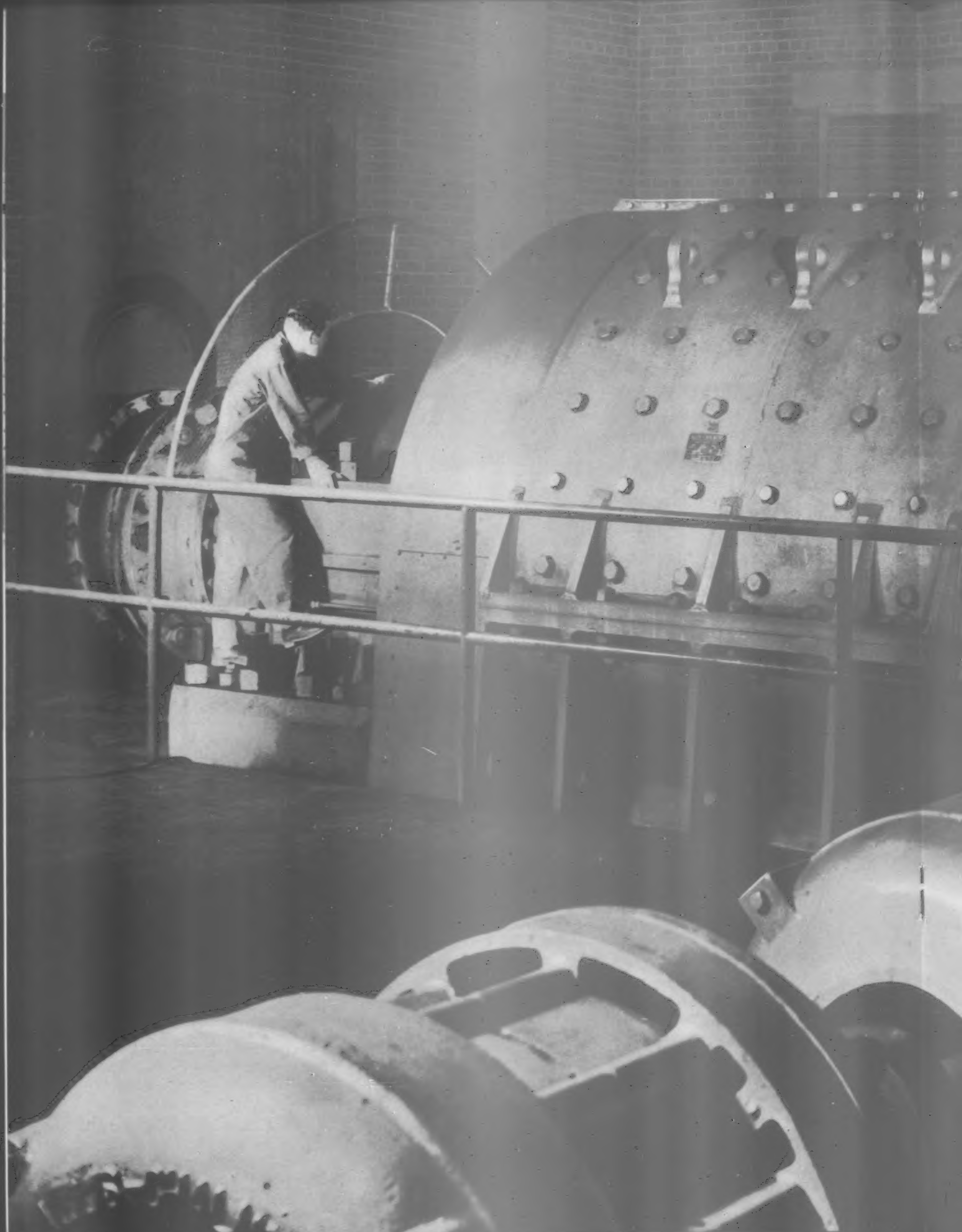


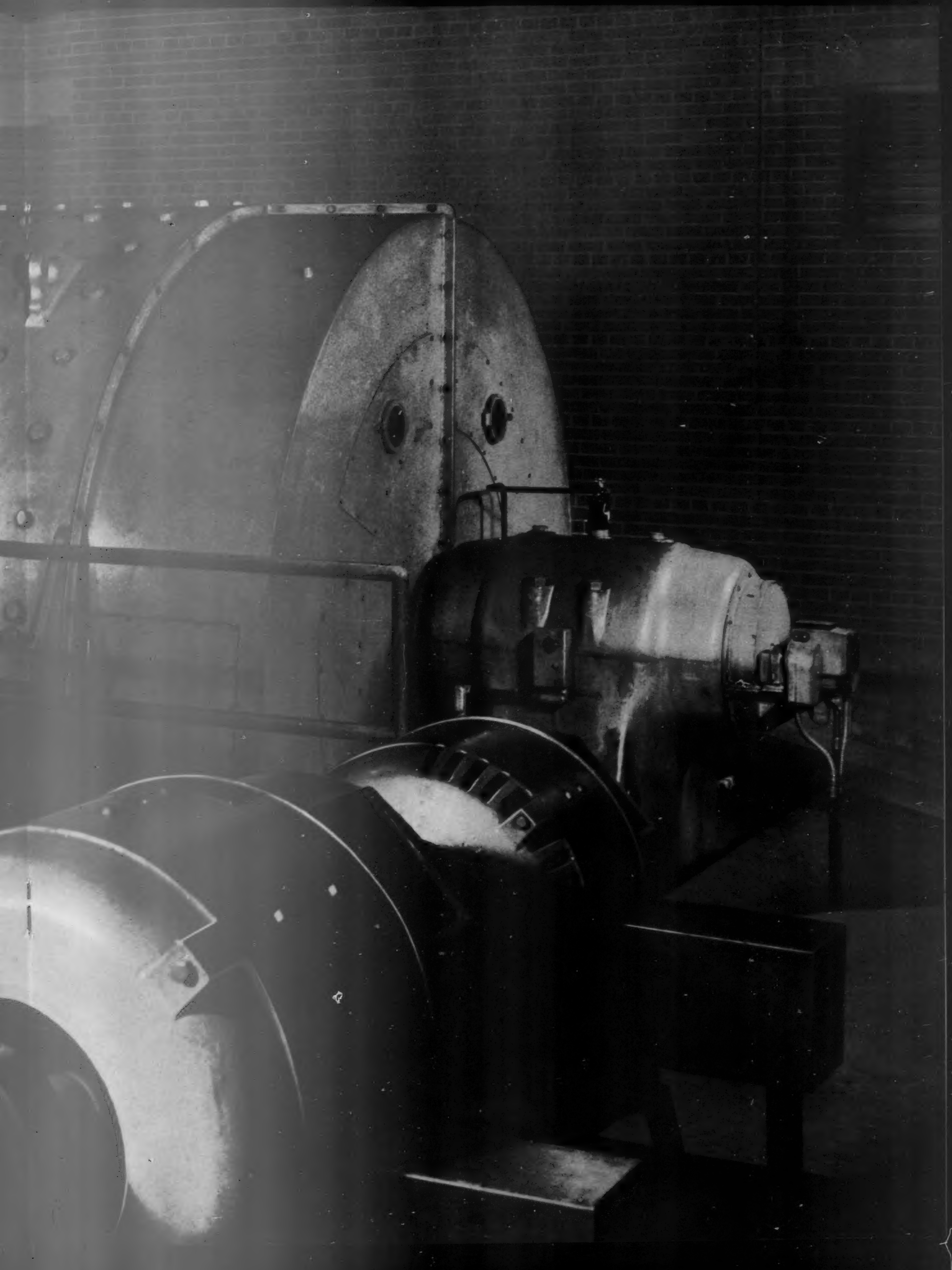
(b)

consisting of a watthour meter, ammeter and an ammeter switch. Besides serving as a check on loading, these instruments are used in keeping power costs for the department served by the load center. One section is devoted to a lighting switch and lighting panel. Lighting is supplied from a secondary transformer located in the secondary substation. The transformer is of the unit type, having primary and secondary switches integrally assembled in the unit. It has been found convenient to use three-phase, 208/120-volt, four-wire transformers for lighting loads. The three-phase unit permits better load balance while providing a source of power for some three-phase motors, such as are found quite frequently in chemical plant laboratories and on small fans, pumps and compressors.

Associated with the 300- or 500-kva power transformer in the substation, lighting transformers rated at 75 or 100 kva have proven economically suitable to serve the areas including the power load. The secondary substation built up in this fashion is flexibly and readily installed; requiring a minimum of space. It can be located outdoors or in a ventilated vault indoors close to the load. When enclosed, the unit substations require no fences, provided switch compartment doors are provided with locks. The location of all process feeder breakers at the substation centralizes control in areas which can be safely reached in all emergencies. Supplies to buildings and process area can be interrupted with little or no hazard to personnel.

STEEL MILLS require varying amounts of power to operate processing equipment. This 4,000-hp, 0/50/120-rpm, 700-volt motor, one of three similarly rated units installed in a Utah mill, drives a 32 by 70-inch, two-high blooming mill (reversing).





Fundamentals of AC

PART TWO OF FIVE PARTS

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The author analyzes the nature of forces which an interrupting device must overcome.

ALTERNATING CURRENT circuit interruption is a two-step process accomplished by first inserting a section of gaseous conductor into the circuit by drawing an arc, and then deionizing the gaseous arc path sufficiently to prevent reignition of the arc after a current zero.

It is also true that, if an a-c arc is to be extinguished immediately after any particular current zero, the values of the growing dielectric strength of the arc gap must continue to exceed the values of the increasing voltage impressed across the gap by the circuit.

The next consideration is the evaluation of the task which an interrupting device must accomplish — of the forces with which it must contend.

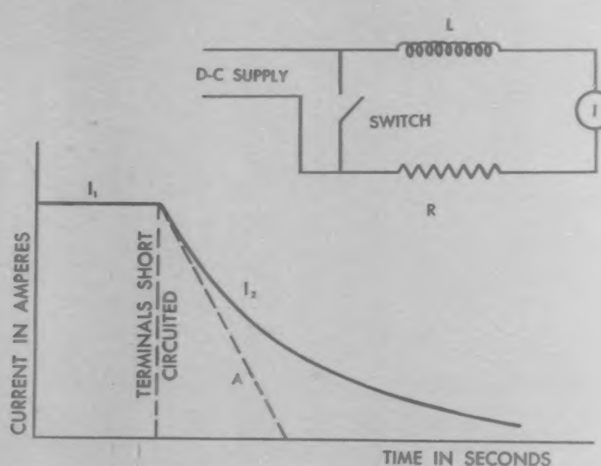
The conditions with which an interrupting device must cope are dictated by the electrical characteristics of the circuit, of which the interrupting device is itself a part. Circuit interrupting devices not only operate during, but also by their operation accomplish rapidly changing circuit conditions. Therefore, the transient characteristics of both the circuit and the interrupting device are vital factors in the determination of any particular interrupting process.

Electrical inertia produces transients

Normally, any electric system is in a balanced or steady-state condition. In other words, the rms values of current flowing and the rms values of voltage obtaining at each and every point in the system are normally constant. This condition persists as long as no change is made or occurs in the constants of the circuit, including its connected supply and its connected load.

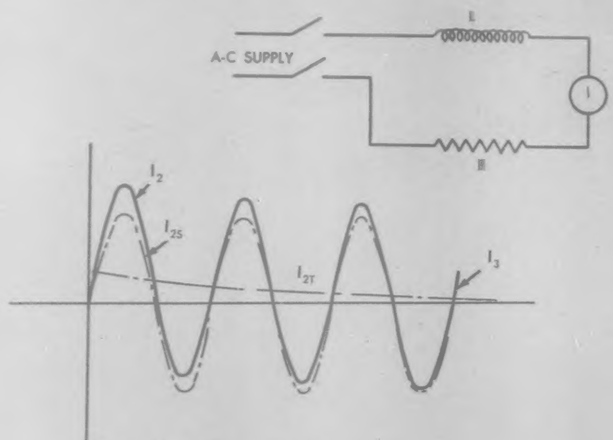
Every electric circuit, however, possesses the characteristic of electric inertia to a degree depending principally upon its inductance (L) and capacitance (C). Both inductance and capacitance store energy and affect the rate of current flow (i), the rate of change of current flow $\left(\frac{di}{dt}\right)$ as well as the phase angle between the current and voltage. When system or circuit conditions change, the circuit may either give up some or all of its stored energy, or store additional energy, in a way depending upon relative values of (L) and (C). Resistance only affects the rate of current flow.

Whenever a change in conditions takes place in an electric system, an electrical unbalance results temporarily and, due



I_1 = Initial steady-state current
I_2 = Transient current
A = Slope of transient current at time of short-circuit

CURRENT TRANSIENT for a single d-c inductive (RL) circuit shown above is simpler than transients in a-c circuits. Short-circuiting terminals gradually dissipates the original steady-state current. **(FIGURE 1)**



I_2 = Resulting transient current
I_{2S} = Final steady-state component
I_{2T} = Transient (exponential) d-c component
I_3 = Final steady-state current

CURVE SHOWS both the a-c and d-c components of the current transient in a circuit containing resistance and inductance but no capacitance. The transient current wave I_2 is asymmetrical. **(FIGURE 2)**

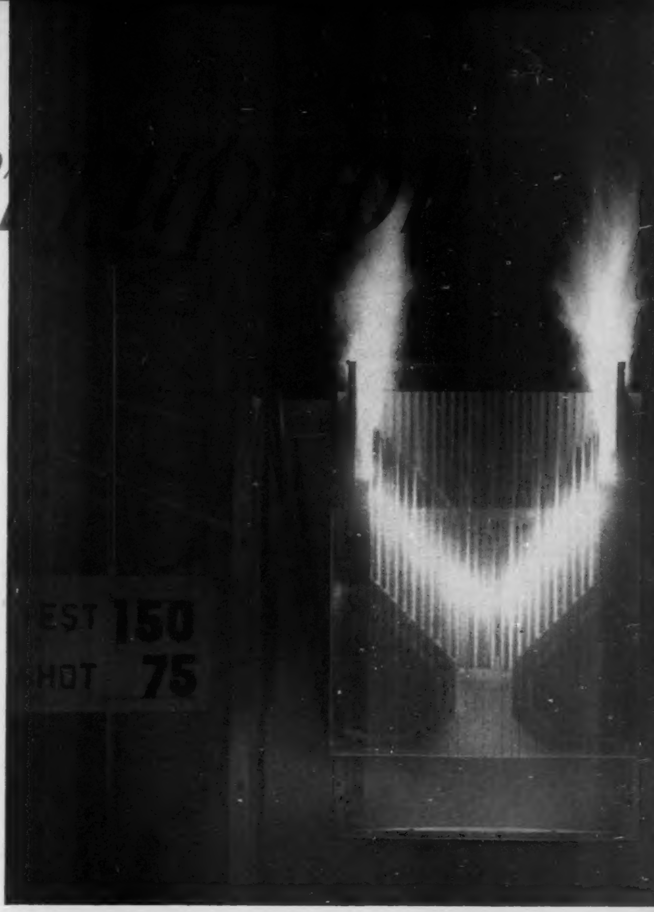
Circuit Inte

to the circuit inertia, time is required for the electrical quantities to readjust themselves to a new balanced, or steady-state condition. Transient conditions prevail in the system during this interval.

An initial steady-state condition in a circuit might be characterized by an initial steady-state current I_1 and an initial steady-state voltage V_1. A final steady-state condition in the same circuit might be characterized by a final steady-state current I_3, and a final steady-state voltage V_3. During the intervening transient period, the current would change from I_1 to I_3, and the voltage would change from V_1 to V_3, in a way which depends upon the characteristics of the circuit. The transient current may be designated by I_2 and the transient voltage by V_2.

Thus, wherever a change occurs in an electric system, the initial steady-state will give way to transient-state conditions which, in turn, will give way to final steady-state conditions.

Obviously, any fault in an electric system, as, for instance, a line-to-ground fault, or a short circuit between phases, is a change upsetting its initial steady-state. Similarly, the initial steady-state of a system is upset by the operation of an interrupting device resulting in interruption of current flow.



TESTS TO DESTRUCTION are a part of developing new circuit breaker designs. Taken in the "bomb house" where tests to destruction are performed, this photo shows sustaining arcing in an experimental structure. The brilliant arc path is visible through the transparent side panel.

Compound transients

Where there is a fault in an electric system, causing an interrupting device to operate, the fault is a first change, and the subsequent interruption of the fault current a second change, of system conditions. Complete interruption of a circuit is often effected during a transient period after an initial steady-state has been upset by a fault. In such a case a final steady-state, as determined by the fault conditions, will never be reached, since complete interruption of the circuit takes place prior to this. The part of the transient lasting from initiation to completion of the interrupting process is a compound transient determined by fault conditions as well as by interrupting conditions.

Thus interrupting devices have to cope with transients, and produce transients with which they have to cope.

Transient currents

Transients in d-c circuits are less complex than transients in a-c circuits and, therefore, lend themselves particularly well to illustrating the fundamental nature of such phenomenon.

Figure 1 refers to an inductive d-c circuit having ohmic resistance but virtually no capacitance (RL circuit) and shows the current transient occurring when the applied voltage is being removed by short circuiting the terminals. The initial steady-state current does not disappear instantly, but dies out according to an exponential curve. The dotted line in Figure 1 indicates the initial rate of decrease of current. If that decrease continued at the same rate, the current would become zero after a time

$$T = \frac{L}{R} \qquad \text{Eq. (1)}$$

where

L = inductance and

R = resistance in the circuit

T is referred to as the time constant of the circuit and is a measure for the duration of the transient condition. The higher the inductance L, the higher the magnetic energy stored in the circuit, and the longer the period required for converting that energy into heat by I^2R losses. In the case under consideration, the transient condition is merely a process of converting the energy of the magnetic field associated with the circuit into heat. The higher the resistance R, the more rapid the dissipation of magnetic energy into heat and the shorter the duration of the transient condition.

Asymmetrical short-circuit currents

Because of their magnitude, short-circuit currents are the most important current transients in circuit interruption.

Electric transients occurring in a d-c circuit while a mag-

netic field is being established or discharged through a resistance (as in Figure 1) or a condenser charged or discharged through an ohmic resistance, may be expressed by a simple exponential equation. The most common current transients in a-c circuits may be considered as the algebraic sum of a transient d-c component (which may be expressed by an exponential equation) and of a steady-state a-c component equal to the final steady-state values. Figure 2 illustrates such a transient and its components.

In this figure, I_{3S} indicates the final steady component, I_{2T} the d-c transient component, and I_2 the resulting transient a-c current wave. The transient component I_{2T} is a d-c current decreasing with time and is responsible for the fact that the major part of the transient current wave I_2 is situated above the zero current axis, i.e. that it is asymmetrical. Note, however, that the transient current I_2 is symmetrical about I_{2T} and that the decrease of the transient component I_{2T} with time, which is referred to as the d-c decrement, permits the final steady-state current I_3 to be symmetrical about the zero current axis.

The character of the transient d-c component I_{2T} in Figure 2 is similar to that of the transient d-c current in Figure 1 and both can be expressed by an exponential equation.

It can be shown that the magnitude of the d-c component and consequently the short-circuit current in an a-c circuit depends upon the point of time (with respect to the voltage wave) at which the short-circuit occurs. This has been illustrated in Figures 3a and 3b.

Figure 3a illustrates the case of a short-circuit occurring at the time when the voltage wave passes through zero, while Figure 3b illustrates a short-circuit occurring at the time when the voltage wave is at its peak value. In drawing these figures it was assumed that the circuit had inductance (L) but no ohmic resistance (R), and was open prior to the occurrence of the short-circuit, i.e. there was no current flowing previous to the short-circuit current. A typical case of that kind would be the closing of a short-circuited system by a circuit breaker. Because the short-circuit in Figure 3a occurred at a zero of the voltage wave (v), the short-circuit current I_2 is entirely above the zero current axis, touching the latter only once per cycle. This current may be interpreted as consisting of the sum of an a-c component i_1'' which lags the applied voltage by 90 degrees, and a constant d-c component i_2'', which raises the a-c component to as high as double its peak value. Since the circuit has been assumed to have no ohmic resistance, no energy will be dissipated in the circuit and the d-c component will not decay. Because the short-circuit occurs at voltage peak the short-circuit current I_2 in Figure 3b is a normal a-c current, i.e. it has no d-c component.

The reason underlying the phenomenon illustrated in Figures 3a and 3b is readily apparent when considering that in the case of an entirely inductive circuit (having no resistance) the circuit voltage (e) is proportional to the circuit inductance (L) times the rate of change of current $\left(\frac{di}{dt}\right)$, from which it follows that the current is proportional to the integral of the voltage wave. Hence, in Figures 3a and 3b, the amplitudes of the short-circuit current waves I_2 are proportional to the accumulated area under the voltage wave (v). Since in the case of Figure 3a the voltage (v) continues to act in the same direction after the first quarter cycle of the voltage wave, the short-circuit current (I_2) continues to rise after that point of time. In the case of Figure 3b the voltage wave (v) changes its direction after the first quarter cycle (adding negative area) and therefore the short-circuit current begins to decrease at that point of time.

Figure 4 illustrates the common case of a-c transients occurring in an RL circuit where, due to the presence of resistance, the d-c component decays.

A-C transient component

Transient a-c currents may also have a-c transient components. Obviously, these may be the result of changing, or transient, reactance.

Figure 5 illustrates an extreme case of this type of transient which occurs on short-circuiting an a-c generator, and it refers in particular to the closing of a generator on a short-circuit at a time when the generated voltage passes through its peak. On occurrence of the short-circuit the current rises rapidly, its rise being limited only by the leakage reactance of the generator stator, or the sub-transient reactance. The large stator current sets up a magnetic field which tends to wipe out the air gap flux. In changing, the air gap flux generates electromotive forces in the rotor windings and eddy currents in the pole faces tending to maintain the air gap flux.

As energy is gradually being dissipated in the system, a final steady-state is gradually being reached. The final steady-state current I_3 is much lower than the transient current I_2 and may be, for instance, in the order of four times the rated full load current of the generator. The transient current I_2 is the algebraic sum of a transient a-c component $I_{2T\,a\text{-}c}$ decreasing with time to zero and of a steady-state a-c component equal to the final steady-state current I_3. The decrease with time of the transient component $I_{2T\,a\text{-}c}$ is referred to as the a-c decrement.

Both a-c and d-c transient components

In the case of a short-circuit on a system including an a-c generator, an a-c transient component will be present although it may be small, as shown in Figure 6. A d-c transient component may or may not be present as shown in Figures 2, 3, or 4, depending upon the point in the voltage wave at which the fault is initiated.

Figure 6 illustrates, diagrammatically, a highly asymmetrical short-circuit current of this type occurring in electric circuits having ohmic resistance in addition to inductance. The transient short-circuit current I_2 comprises an a-c com-

ponent and a transient d-c component $I_{2T\,d\text{-}c}$ decreasing with time. The a-c component in turn is made up of a final steady-state a-c component and a small transient a-c component identification of which has been omitted in the figure for clarity. It can be determined, however, from the fact that the dotted envelope lines are father apart at T_0 than at T_1.

Figure 6 refers to a short-circuit occurring at the time of a voltage zero and should be compared with the similar case of Figure 3a wherein the d-c component does not decay since there are no losses in the circuit.

Figure 7 is an oscillographic record made with a 150,000-kva interrupting capacity, 5,000-volt, magnetic air break circuit breaker when interrupting a highly asymmetrical short-circuit current. At the time when the contacts part, the d-c transient component of the current is still quite large. The rms interrupted current is 3,770 amperes at 2,500 volts, and the arcing time .75 cycles.

This oscillogram illustrates the case of a compound transient previously mentioned. Referring to the point of time identified "Contacts Part," it will be noted that the fault current is not yet symmetrical about the current zero axis, indicating that the transient d-c component of current has not yet decayed to zero. In other words, the circuit is still in a transient state initiated by the occurrence of the fault, when a second change in circuit conditions is initiated by the operation of the breaker.

This record also illustrates one effect of a characteristic of an interrupting device upon the duty which it must itself perform. It appears from Figure 7 that the last half-cycle of fault current just previous to circuit interruption is much smaller than an envelope line drawn through the preceding negative current peaks would indicate it should be. This reduction in fault current by the interrupting device is caused by the development of high arc resistance. Confirming evidence of this is the high arc voltage loop for the same half cycle which appears just above the small current loop.

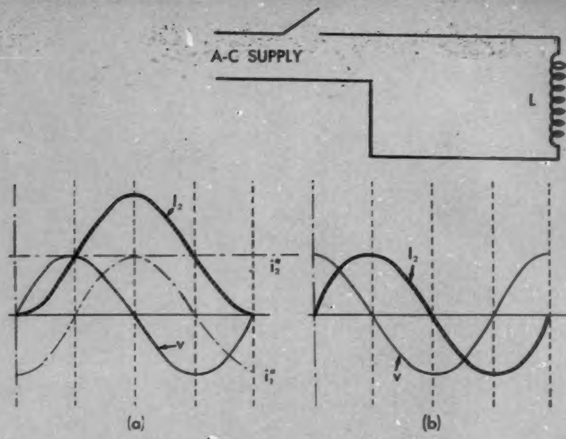
Figure 8 is similar to Figure 7 except that a large a-c decrement as well as a large d-c decrement is shown. The effective value of an asymmetrical a-c current at any instant is equal to the square root of the sum of the squares of the effective values of the a-c and d-c components.

Effect of short-circuit current transients

The decrement characteristics of a system or circuit affect the duty of an interrupting device in different ways.

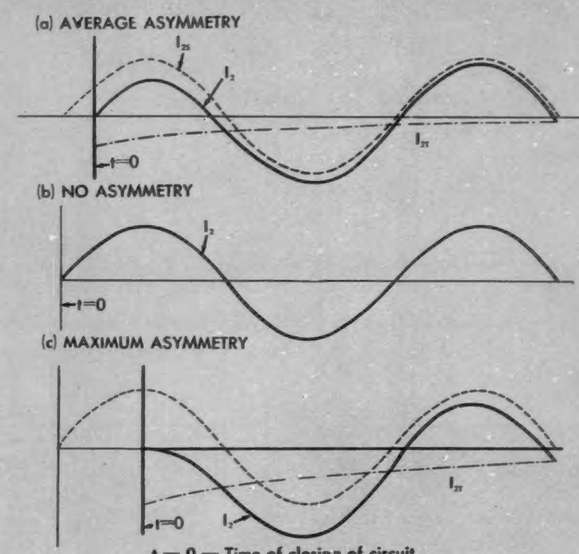
The first is the effect on the voltage tending to re-establish the arc current after a zero of the current wave known as transient recovery voltage. This effect will be discussed in the next installment of this article.

The second effect of the decrement characteristic is in connection with the value of current actually interrupted particularly in the case of interrupting devices having several cycles of arcing. For purposes of duty determination and



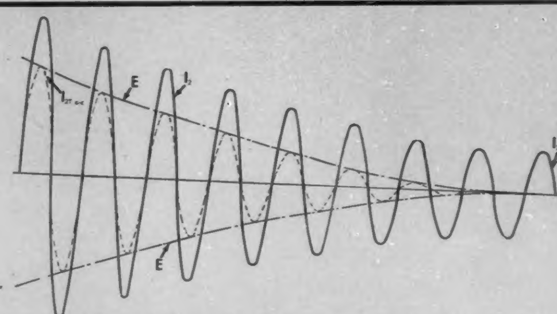
v = Circuit voltage
I_2 = Short-circuit current
i_1'' = A-c component of short-circuit current
i_2'' = D-c component of short-circuit current

COMPARATIVE CHARACTERISTICS of a short-circuit occurring at the point of time of voltage zero (a) and at the point of time of peak voltage (b) in a purely inductive circuit. **(FIGURE 3)**



$t = 0$ = Time of closing of circuit
I_2 = Current (transient)
I_{2T} = Transient d-c component
I_{2S} = Final steady-state component

SHAPE OF CURVE of transient currents during closing in an inductive (RL) a-c circuit depends upon the point of time relative to the voltage wave at which the circuit is closed. **(FIGURE 4)**



I_2 = Transient short-circuit current
I_3 = Final steady-state short-circuit current
$I_{2T\,a\text{-}c}$ = Transient a-c component of short-circuit current
E-E = Envelope of transient component

SYMMETRICAL TRANSIENTS, such as that shown above, occur when an a-c generator is short-circuited at the time of peak voltage. The decrease with time of the transient $I_{2Ta\text{-}c}$ is known as the a-c decrement. **(FIG. 5)**

interrupting device rating, the current is measured at the first half cycle of arcing. Where there is a considerable decrement which persists through a relatively long arcing time, the average current through the arcing time may be appreciably less than the initial current in the arc, upon which the interrupting duty is based. As shown in Figure 7, the current may be reduced during the arcing time to a greater extent than can be attributed to the decrement. The way in which the current is decreased during the arcing time to smaller values than those attributable to the decrement, is a characteristic feature of any particular piece of apparatus.

As stated above, the current interrupting duty and rating of an interrupting device are determined by the current during the first half-cycle of arcing. Because of the decrement, the current during the first half-cycle of arcing may be less than the short-circuit current which an electric system is capable of producing. Thus the current which an interrupting device is required to carry, or to close in against on a close-open operation, may well exceed the current which the device is required and rated to interrupt.

Factors determining short-circuit currents

The main factors determining the value and duration of short-circuit currents are the connected supply capacity, the impedance of both the power sources and of the portion of the circuit situated between the sources feeding power and the point of short-circuit, and the characteristics of rotating machinery connected to the system at the time the short-circuit occurs.

Synchronous motors and induction motors as well as synchronous generators constitute sources of short-circuit currents. At the time of short-circuit motors act as generators and feed energy into the short circuit, often contributing an important share of the total short-circuit current. Synchronous motors receive their normal excitation at the time the short-circuit occurs and operate as generators by reason of the inertia inherent in their moving parts. It takes time for the flux in the secondary of the core of an induction motor to vanish, and during that time energy will be inductively supplied from the motor to the short circuit.

Problems involved in short-circuit currents

Short-circuits are caused by faults in the insulation of a circuit, and in many cases an arc ensues at the point of the fault. Such an arc may be destructive and may constitute a fire hazard, and this is one among the reasons requiring interruption of a faulted circuit.

A heavy short-circuit current generates heat which, as the heat generated by any other current, is proportional to the square of the current strength. The large amount of heat generated by a short-circuit current may endanger any rotating machinery and apparatus which is connected into the faulted system, including transformers, switches, and circuit breakers. The most immediate danger involved in the heat generated by short-circuit currents is permanent destruction of organic insulation. This may be followed by actual fusion of the conducting circuit, with resultant additional arcing faults.

Other important effects of short-circuit currents are the strong electromagnetic forces of attraction and repulsion to which the conductors are subjected when short-circuit currents are circulating. These forces are proportional to the square of the current and may subject any rotating machinery and apparatus which is connected to the faulted system, including switches and circuit breakers, to severe stresses and strains.

Prolonged arcing — whether it occurs at the point of a short-circuit or in an interrupting device — may result in building up of overvoltages which may endanger the insulation of the system. This hazard is another reason which may compel rapid interruption of a faulted circuit.

Modern interconnected systems involve the operation in parallel of large numbers of synchronous machines, and the stability of such an interconnected system may be greatly impaired if a short-circuit in any part of the system were allowed to prevail for any length of time. Quite often the stability of a system may require considerably shorter clearing times than considerations imposed by thermal or mechanical reasons would require. The interrupting times of modern power circuit breakers, i.e. the time elapsing between energizing the trip coil and complete interruption of the circuit, vary within the range of three to eight cycles.

Thermal effects of short-circuit currents

The heat which is generated by high short-circuit currents tends not only to impair insulating materials to the point of permanent destruction, but also exerts harmful effects upon the contact members in interrupting devices.

The area of the relatively few and small surface elements common to two cooperating contact members which are in engagement depends mainly upon the hardness of the contact material and upon the amount of pressure by which they are kept in engagement. Owing to the concentration of the flow of current at the points of contact engagement, the temperatures which these points reach at the times of peak currents are very high. As a result of these high spot temperatures, the material of which the contact members are made may soften, causing an increase in the total area of contact engagement and passage of current flow, and consequent reduction of I^2R losses and of temperature.

If, however, the contact material is caused to melt by excessive I^2R losses, there is an imminent danger of welding the contacts together, an effect which is known as "contact freezure." It is evident that "contact freezure" may render it impossible to separate the contact members when the switch or circuit breaker is called upon to open the circuit. Since it requires but very little time to establish thermal equilibrium at the small points of contact engagement, the temperature at these points depends more upon the peak current than upon the rms current. If the peak current is sufficient to cause the contact material to melt, resolidification may occur immediately upon decrease of the current from its peak value, since the time for establishing thermal equilibrium may be extremely small.

Electromagnetic forces

The strong electromagnetic forces which high short-circuit currents exert upon cooperating contact members of a switch or circuit breaker often tend to cause their separation. Hence it is necessary to provide means for preventing excessive reduction of contact pressure or unintended or premature separation of contact members due to electromagnetic forces resulting from high short-circuit currents.

There are two general ways of solving that problem. One of them consists in designing the contact carrying structure with such strength that it is capable of withstanding the maximum short-time forces to which it is subjected. This must, of course, be done without adverse effects upon the contact members. The other way consists in so designing the path of the current through the switch or circuit breaker so that the electromagnetic forces resulting from any current flowing through it will be mutually balanced and compensated.

Short-time ratings

The standard short-time overcurrent ratings define the methods of determining the ability of interrupting devices to withstand the thermal and electromagnetic effects of high transient currents.

Power circuit breakers are designed to meet a momentary current test at a value (including d-c component) usually about 1.6 times their maximum rated interrupting current for 8-cycle breaker, 1.45 times for 5-cycle breakers, and 1.35 times for 3-cycle breakers. These factors have been selected as the maximum ratios normally encountered in practice. This momentary current test is primarily indicative of the ability of the device to withstand the electromagnetic effects of the high inrush currents.

A second high current test standard is the five-second rating (likely to be changed to a two-second rating) at a current value equal to the maximum interrupting rating in amperes. This longer time high current test is primarily indicative of the ability of the device to withstand the thermal effects of high current.

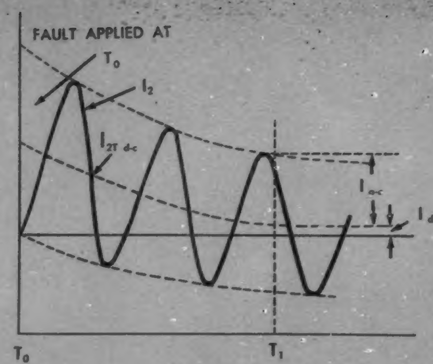
Summary

In this installment we have considered transient conditions in electrical systems, particularly transient short-circuit currents and their effects upon the conditions under which an interrupting device must perform.

We have seen that circuit interrupting devices must deal with transient currents, and may themselves affect the transient currents with which they are dealing.

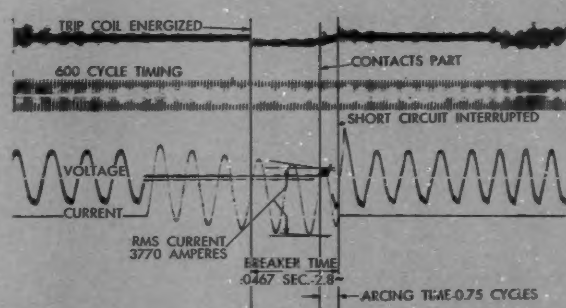
Some of the effects of short circuit currents have been discussed as well as the importance of interrupting them before they cause great damage.

(In the next installment Dr. Salzer will discuss transient voltages, including that most important factor in circuit interruption — transient recovery voltage and its rate of rise.)



$I_{a\text{-}c}$ = A-c component at instant T_1
$I_{d\text{-}c}$ = D-c component at instant T_1

SHORT-CIRCUIT CURRENTS occurring in electrical circuits having ohmic resistance in addition to inductance are completely asymmetrical, as shown above. The a-c decrement is small. **(FIGURE 6)**



OSCILLOGRAPHIC RECORD showing the characteristics of asymmetrical short-circuit current and its interruption by magnetic air break circuit breaker. Voltage is measured directly across breaker. **(FIGURE 7)**

I_{LT_1} = Major deflection (from zero) at T_1

I_{ST_1} = Minor deflection (from zero) at T_0

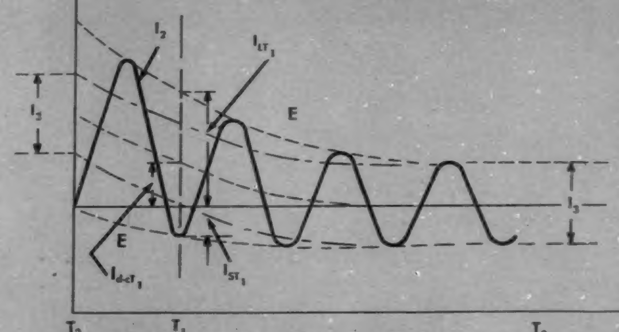
$I_{2T_1} = I_{LT_1} + I_{ST_1}$ effective value of current at $T_2 = \frac{I_2}{2\sqrt{2}}$

Effective (R.M.S.) current at T_1 = square root of sum of squares of a-c and d-c components (effective)

Effective a-c component at $T_0 = \frac{I_{2T_1}}{2\sqrt{2}}$

Effective d-c component at $T_1 = \frac{I_{LT_1} - I_{ST_1}}{2} = I_{d\text{-}cT_1}$

Effective current at $T_1 = \sqrt{\left(\frac{I_{2T_1}}{2\sqrt{2}}\right)^2 + \left(I_{d\text{-}cT_1}\right)^2}$



ENVELOPE E-E of this transient current has both a-c and d-c decrements. Transient current I_2 decays to final steady-state, peak-to-peak value I_3 at time T_2. Decrements are both large. **(FIGURE 8)**

THE ONE-THOUSANDTH REGULATOR made on a production-line established less than a year before is nearing completion in this photo taken recently at the Allis-Chalmers West Allis Works. Step-type feeder voltage regulators, unknown fifteen years ago, have become standard equipment on many utility systems. Chief among their advantages are the much higher efficiency and greatly reduced maintenance.

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Short Circuit Calculations *for Circuit Breakers*

ROBERT E. BURLINGAME*
Switchgear Section
Allis-Chalmers Mfg. Co.

Understanding of short circuit values aids selection of suitable interrupting equipment.

SELECTION of proper ratings of circuit breakers and switchgear involves considerable investigation if all operating requirements are to be met adequately and safely. Knowing in general the size and type of equipment which should be used is essential but not necessarily sufficient. Short circuit characteristics of the electrical apparatus to be controlled by the circuit breakers, procedure for short circuit calculations and principles of circuit breaker application constitute the information and knowledge which the prospective purchaser should have at hand and properly apply in order to select correctly safe and adequate circuit breaker ratings.

Selecting circuit breakers

Several characteristics must be given consideration before a circuit breaker is decided upon. These factors are:

1. Voltage rating
2. Continuous ampere carrying capacity
3. Interrupting capacity in kva
4. Maximum ampere interrupting capacity
5. Momentary ampere rating

Voltage rating has reference to insulation required between the individual poles of the circuit breaker and between live parts and other metallic parts such as the tank or frame and the operating mechanism.

Continuous ampere carrying capacity is related to the normal maximum ampere load to be carried at times other than when fault conditions exist.

Interrupting capacities in kva and maximum amperes refer to the maximum fault kva and current which the circuit breaker may be called upon to interrupt.

The momentary ampere rating of a circuit breaker is an expression of the maximum amperes which a circuit breaker is guaranteed to be thermally and mechanically capable of carrying safely for one second, or any lesser period of time. This applies to currents carried but not to be interrupted by the circuit breaker.

In addition to selecting a circuit breaker having voltage and continuous current carrying capacity ratings at least equal to and preferably exceeding the maximum swings of the service voltage and the maximum ampere load, it is also necessary that the kva interrupting capacity, maximum ampere interrupting capacity, and momentary ampere ratings of the circuit breaker at least equal and preferably exceed respectively the maximum short circuit kva, the maximum short circuit amperes to be interrupted, and the initial total rms short circuit current.

Short circuit currents explained

A generator will deliver a short circuit current considerably greater than its rated full load current if the generator terminals are short circuited while the machine is in operation. Similarly a transformer will deliver a short circuit current considerably greater than its rated full load current if its secondary terminals are short circuited while the primary terminals are connected to a source of power. In each case, the short circuit current is limited by the resistance and reactance of the apparatus. In generators the resistance is small compared to the reactance. Hence the reactance is considered as the entire current limiting characteristic in practical calcula-

LARGE INDUSTRIAL NETWORKS require careful study to determine circuit breaker overload requirements. This metal-clad switchgear provides primary control for eight 750-kva load center substations placed at heavy load centers in a large automobile manufacturing plant.

* Mr. Burlingame joined J. F. Pritchard & Co., Kansas City, Mo., as an electrical design engineer shortly after this article was written.

tions. In the case of transformers the impedance (or sometimes reactance) is used as the current limiting characteristic.

In this instance, the percent reactance of a generator may be considered as a percentage expressing the ratio of normal full load current to the current which the generator will deliver into a short circuit at its terminals.

The percent impedance of a transformer may be considered as a percentage expressing the ratio of normal full-load current to the current which the transformer will deliver into a short circuit at its secondary terminals while its primary terminals are supplied with power at full rated voltage.

Motors fed from a bus will function similarly to generators on the occurrence of a short circuit and will contribute to the short circuit current flowing into a faulted feeder served by that bus.

A three-phase current-limiting reactor is considered as having a specified percent reactance at a particular kva load. This means that the voltage drop across each phase of the reactor will be the specified percent of normal phase-to-neutral voltage when the stated kva load is being transmitted through the reactor. Since the voltage drop will vary with the kva load the percent reactance must be qualified by statement of the kva load at which it applies.

The percent reactance of a rotating machine or the percent impedance of a transformer is expressed on a basis of its full load kva rating. Each reactance or impedance used in short circuit calculations is expressed in terms of percent based on a specific kva value, and a kva value used in this manner is referred to as a "kva base." In calculating the short circuit energy obtainable from or through an individual electrical apparatus unit the kva rating of that unit is used as the kva base. A common kva base for several units may be used where a number of them are involved and calculations pertain to moderately complex cases.

Data used in calculations

At least some and occasionally all of the following data is necessary for short circuit calculations:

a) One line connection diagram of power system under consideration
b) Full load kva ratings of all machines, transformers, and reactors
c) Subtransient reactances of generators
d) Transient and subtransient reactances of synchronous motors, synchronous condensers, and synchonous converters
e) Impedances of transformers
f) Reactances of reactors
g) Subtransient reactances of induction motors
h) Reactances or impedances of lines and cables of appreciable length

Values c, d, e, f, and g are usually available in terms of percent reactance or impedance at rated full load kva. The values of h are usually available in terms of ohms reactance and resistance or in terms of circuit length and conductor size, material, and spacing.

Item g is used only in calculating momentary short circuit values and in calculating short circuit values for low voltage air circuit breaker application.

It is preferable to use the actual reactance and impedance data for the particular apparatus under consideration but, in the absence of such data, average data for approximate calculations may be obtained from Tables 2 to 6 inclusive. However, caution should be exercised for the reason that a considerable number of machines and transformers have reactances and impedances substantially lower than the average values indicated by such sources of information and hence enable more severe short circuits than average apparatus.

In most apparatus and lines the resistance is quite small compared to the reactance and may be neglected with but little error. For this reason only the reactance of the circuit elements is usually considered in short circuit calculations. However, in three conductor cables, cables in conduit and very light overhead lines the resistance is appreciable relative to the reactance and may be as great. For such circuit elements impedance may be used instead of reactance. In the usual case such impedances may be added arithmetically to the reactances of the rest of the system with but moderate error.

General calculating procedure

Calculation of short circuit values consists of the following several steps:

1) Calculation of initial symmetrical short circuit value.
2) Multiplication of initial symmetrical value by the proper factor from Table 1 to compensate for displacement of the current wave and for decrement effect to thus obtain a short circuit value such as would exist at the moment of parting of the circuit breaker contacts. The value so obtained must be at least equalled and preferably exceeded by the interrupting capacity of a properly applied circuit breaker.
3) The momentary short circuit value is a maximum total rms initial value and is calculated in the same manner as described above except that a different multiplying factor is selected from Table 1 as is indicated in the table, and the value is converted from kva to amperes (see formula paragraph 5). The momentary ampere rating of the circuit breaker must not be exceeded by the momentary short circuit value.
4) A correctly applied power circuit breaker must not only have a kva interrupting capacity not exceeded by the short circuit kva to be interrupted but must also have a maximum ampere interrupting capacity not exceeded by the short circuit amperes to be interrupted. The second of these requirements must be checked in all cases where the service voltage is substantially less than the rated voltage of the circuit breaker. The short circuit amperes may be calculated from the short circuit kva as indicated in the formula of paragraph 5 and the maximum ampere interrupting rating of the circuit breaker may be obtained from tables of circuit breaker data. Such tables also usually include the minimum service voltage down to which the circuit breaker has full rated kva interrupting capacity.

Example: A 2,400-volt feeder having a maximum load of 400 amperes is fed from a bus which can deliver a maximum of 133,000 short circuit kva.

Initial consideration might indicate that a 600-ampere, 15,000-volt, 150,000-kva interrupting capacity

circuit breaker would be suitable for this feeder. However, further checking reveals that there would be about 32,000 maximum short circuit amperes to be interrupted and that this circuit breaker has a maximum ampere interrupting capacity of only 25,000 amperes and would, therefore, be inadequate. The 1,200-ampere, 15,000-volt, 150,000-kva interrupting capacity circuit breaker has a maximum ampere interrupting capacity of 37,500 amperes and would hence be the proper choice. The minimum voltage for full kva interrupting capacity is 3,500 volts for the 600-ampere circuit breaker and 2,300 volts for the 1,200-ampere circuit breaker. At 2,400 volts the 600-ampere circuit breaker would have an interrupting capacity of only about 104,000 kva.

5) Short circuit values may be conveniently calculated in terms of equivalent short circuit kva but these values are converted into terms of amperes at service voltage for use in applying low voltage air circuit breakers, in checking momentary rating requirements, and for comparing short circuit amperes with the maximum ampere interrupting limitations of power circuit breakers. Conversion from kva to amperes is calculated as follows:

$$\text{Short circuit amperes} = \frac{\text{short circuit kva}}{\sqrt{3} \times \text{service kv}}$$

The short circuit kva from which power circuit breaker interrupting capacity requirements are determined is equivalent three-phase kva calculated from service voltage (phase to phase) and the maximum amperes to be interrupted by any pole of the circuit breaker.

CAUTION: When the system under consideration has a grounded neutral be sure to check values of "phase to ground" faults. These are discussed under "Calculations for Grounded Neutral Systems."

Calculating simple cases

Isolated generating station: (See Figure 1)

a) Obtain percent subtransient reactance of each generator at rated full load kva and calculate the short circuit contribution of each generator as follows:

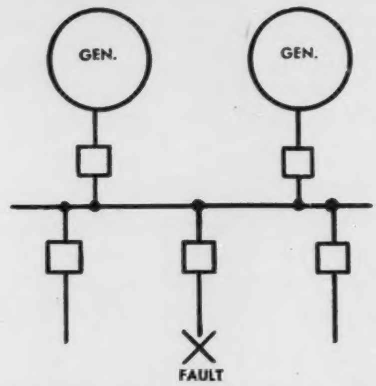
$$\text{Initial symm, short circuit kva} = \frac{\text{rated kva} \times 100}{\%\ \text{subtran. reactance}}$$

b) Total the respective short circuit contributions of the several generators to obtain the maximum initial symmetrical short circuit kva which a feeder circuit breaker may be subjected to.

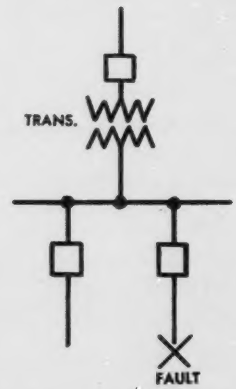
c) Proceed as outlined under "General Calculating Procedure."

Secondary side of transformer substation: (See Figure 2)

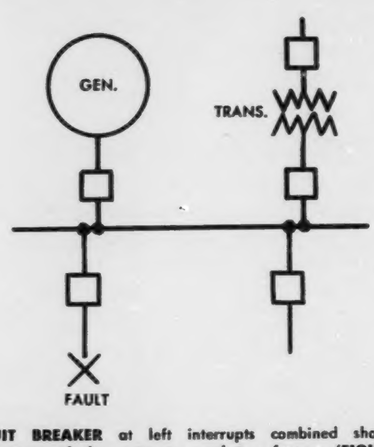
a) Obtain the value of maximum short circuit kva available at the primary terminals of the transformer, the kva rating of the transformer (three-phase), and the percent impedance of the transformer at that rating. If the substation is served from a power company line, reliable primary short circuit data is usually obtainable from the power company. If not and data from a reliable source includes the required interrupting capacity of the primary circuit breaker ahead of the transformer, this value may be considered to be the short circuit kva at



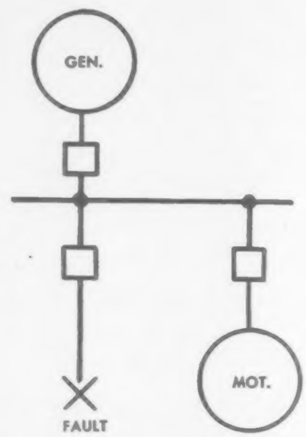
SIMPLIFIED LINE diagram of an isolated generating station having two generators and three outgoing feeders. **(FIGURE 1)**



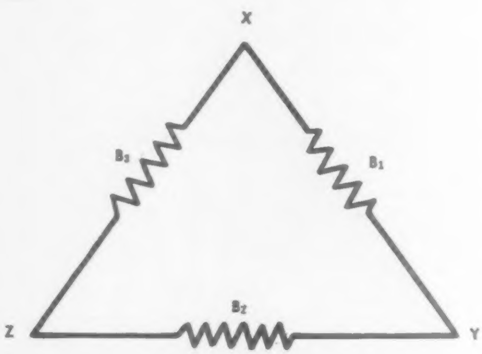
ELEMENTARY DRAWING of a transformer substation with one three-phase transformer and two outgoing feeders. **(FIGURE 2)**



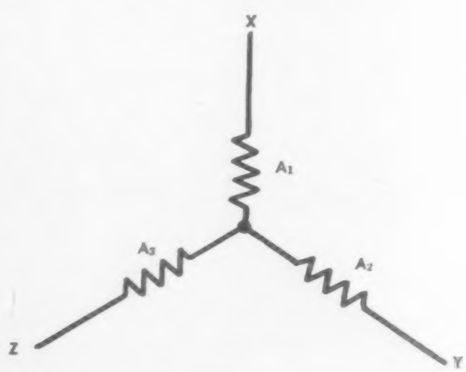
CIRCUIT BREAKER at left interrupts combined short circuit currents of the generator and transformer. **(FIGURE 3)**



SHORT CIRCUIT currents of motor and generator flowing into fault must be interrupted by the feeder breaker. (FIGURE 4)



GROUP OF REACTANCES arranged in delta configuration. Arrangement simplifies short circuit calculations. (FIGURE 5)



STAR CONFIGURATION shows connection of three circuit elements between points of a power system. (FIGURE 6)

the primary terminals of the transformer. If no information is available concerning the short circuit conditions at the primary terminals of the transformer, it is best to neglect line impedance and make calculation on the basis of the transformer impedance being the total impedance.

b) Calculate the percent impedance of the primary supply circuit on a kva base equal to the rated kva of the transformer as follows:

$$\% \text{ impedance} = \frac{\text{transformer kva} \times 100}{\text{short circuit kva on primary}}$$

c) Add the supply circuit percent impedance and the transformer percent impedance and use the total to calculate the initial symmetrical short circuit kva as follows:

$$\text{Initial symm. S. C. kva} = \frac{\text{transformer kva rating} \times 100}{\text{total percent impedance}}$$

d) Proceed as outlined under "General Calculating Procedure."

Combinations of sources: (See Figures 3 and 4)

a) Where a bus is fed directly from generators and also from other sources through transformers the short circuit contributions of both types of sources, calculated as described in paragraphs 1 and 2 above, may be added together to determine the short circuit kva which a feeder circuit breaker may be required to interrupt.

b) Where synchronous motors, synchronous condensers, or synchronous converters are involved, their short circuit contributions may be calculated as outlined above for generators but using transient rather than subtransient reactance. These contributions are added to those from other sources. For synchronous motors the kva ratings are approximately 0.8 kva per hp for 1.0 pf machines and 1.0 kva per hp for 0.8 pf machines. For calculating momentary current contributions of all rotating machines subtransient reactance is used.

c) Where induction motors form an appreciable part of the load, their short circuit contributions must be included where application of low voltage air circuit breakers is involved and where the momentary current rating requirement of power circuit breakers is to be determined. Induction motors may be assumed to have 20 percent subtransient reactance and to have kva ratings of approximately 0.9 kva per hp.

Cases involving cables or lines

Where cables or lines of appreciable length constitute parts of the paths of short circuit currents from sources to the fault location, their impedances should be included with the generator reactances and transformer impedances. If the circuit impedance is not known but the length of the circuit and the conductor size, material, and spacing are known, the impedance may be calculated from data in conductor resistance and reactance tables to be found in the Standard Handbook for Electrical Engineers and other publications. The conductor spacings on which reactance tables are based assume that the conductors are disposed at the corners of an equilateral triangle. Where the actual conductor spacing is other than that

of an equilateral triangle, the equivalent triangular spacing may be obtained through the following equation:

$$\text{Equivalent triangular spacing} = \sqrt[3]{D_1 \times D_2 \times D_3}$$

where D_1, D_2 and D_3 are the actual distances between phase wires.

Calculations in moderately complex cases

Prepare a one line connection diagram of the system under consideration and note percentage of reactance or impedance for each machine, transformer, reactor, and line beside the corresponding symbol in the diagram.

Convert all percentages of reactance and impedance to percentages on a common kva base and note these values on the diagram. Any convenient common kva base may be chosen but a value of the same order as the total power supply capacity of the system is usually preferable. To convert a percent reactance or impedance from a value based on the apparatus kva rating to a percent on a common kva base apply the following equation:

$$\% \text{ on common kva base} = \% \text{ on rated kva} \times \frac{\text{Common kva base}}{\text{rated kva}}$$

Draw another diagram including an infinite source bus in addition to the buses of the original diagram. An "infinite source" is a hypothetical limitless source of electrical energy capable of maintaining normal rated voltage regardless of the magnitude of the load imposed upon it. It may also be described as a source having zero resistance and reactance. Show machines as reactances connected between the infinite source bus and the points in the system to which they were connected in the original diagram. Show transformers, reactors, and lines as reactances and impedances connected between the same points as in the original diagram. Beside the symbol for each circuit element note the percent reactance or impedance on the common kva base.

In the process of calculating short circuit energy in a fault at a given point in the system, the over-all percent reactance from the infinite bus to that point through the network of circuit elements is next determined. To that end the network is simplified by adding reactances which are in series (with no circuits branching off between them) and substituting therefor the resultant equivalent single reactance. Reactances in parallel are combined and replaced by the resultant single equivalent reactance. Reactances in series are combined by simple addition, and reactances in parallel are combined by the following equation:

$$\text{Combined reactance} = \frac{1}{\frac{1}{\text{Reactance}_1} + \frac{1}{\text{Reactance}_2} + \frac{1}{\text{Reactance}_3}}$$

As simplification of the network proceeds, successive new diagrams should be made in which single combined reactances are drawn in place of the groups of reactances for which they are substituted. This process of simplification should be continued until the entire network of reactances has been reduced to a single reactance connected between the infinite source bus and the fault location.

In many instances a reactance network will include a group of reactances arranged in a delta configuration, as shown in Figure 5, or a star configuration, as shown in Figure 6. Simplification of such a network can often be facilitated by convert-

TABLE 1 — MULTIPLYING FACTORS

Interrupting Device	Interrupting Capacity		Momentary Current Capacity	
	General Case	Heavy Duty[1]	5,000 Volts and below[2] except on generator bus	General Case on generator bus or above 5,000 Volts
Power Circuit Breakers[3]				
8 Cycle	1.0	1.1	1.4	1.6
5 Cycle	1.1	1.2	1.4	1.6
3 Cycle	1.2	1.3	1.4	1.6
2 Cycle	1.4	1.5	1.4	1.6
Low Voltage Air Circuit Breakers — 600 v. and below	1.25		1.25	
Power fuses, Cur. Lim. fuses	1.6			

[1] Where the interrupting device is to be connected in a circuit liable to short circuits of more than 500 mva fed predominately either directly from generators or through current limiting reactors, this column should be used.

[2] In circuits at 5,000 volts or below, unless current is fed predominately by directly connected synchronous machines or through current-limiting reactors only, this column should be used.

[3] Circuit breakers used in metal-clad switchgear (up to 500,000 kva interrupting capacity and 15 kv) are rated as eight-cycle circuit breakers, except air blast circuit breakers which have a five-cycle rating.

TABLE 2 — APPROXIMATE REACTANCES OF 3-PHASE, 60-CYCLE ROTATING MACHINES

Type of Machine	Percent Reactance					
	Subtransient X_1		Transient		Zero Sequence X_0	
	Range	Mean	Range	Mean	Range	Mean
Turbo-generators — 2-pole	6-15	9	Not used in normal short circuit calculations		1-8	1
Turbo-generators — 4-pole	12-17	14			1.5-14	3
Engine generators — with damper windings	15-30	20			2-20	6
Waterwheel generators — with damper windings	17-35	25			2-20	6
Waterwheel generators — without damper windings	20-30	30			4-22	8
Synchronous condensers — Air cooled	18-30	25				
Synchronous condensers — Hydr. cooled	21-35	30				
Synchronous converters	15-35	20	20-50	25	2-20	6
Synchronous motors — 720 RPM and above	10-20	17	15-35	25		
Synchronous motors — 600 RPM and below	20-35	30	20-50	40		
Induction motors	15-25	25				

In general, the reactance of a 25-cycle machine will be approximately 80 to 90 percent of the reactance of a corresponding 60-cycle machine. The difference between 50-cycle and 60-cycle machines is small. The effect of induction motors is usually present only in the first two or three cycles.

SWITCHYARD CONSTRUCTION now in progress at Coulee Dam in Washington will have seven 1,500- and 2,500-mva, 115-kv, 800-amp oil circuit breakers in operation upon completion. Principles of circuit interruption remain the same no matter how large the installation may be.

TABLE 3 — APPROXIMATE ZERO PHASE SEQUENCE FACTORS

Apparatus	Multiplying Factor[1] (Number of times ordinary three-phase reactance)
Transformer with grounded neutral	1
Transformer with isolated neutral	Infinity
Single Circuit Aerial Line — No ground wire	3.5
Single Circuit Aerial Line — With ground wire	2
Double Circuit Aerial Line — No ground wire	5.5
Double Circuit Aerial Line — With ground wire	3
Three-Conductor Cable	1-1.5
Single-Conductor Cable	0.5-0.7
Neutral Resistor or Reactor	3

[1] Because local ground conditions vary greatly, the zero sequence factor cannot be predicted accurately.

ing a group of three reactances forming one of the two configurations into three new reactances forming an equivalent group having the other configuration.

A delta group may be converted to an equivalent star group by means of the following equations:

$$A_1 = \frac{B_1B_3}{B_1 + B_2 + B_3} \qquad A_2 = \frac{B_1B_2}{B_1 + B_2 + B_3}$$

$$A_3 = \frac{B_2B_3}{B_1 + B_2 + B_3}$$

A star group may be converted to an equivalent delta group by means of the following equations:

$$B_1 = \frac{A_1A_2 + A_1A_3 + A_2A_3}{A_3} \qquad B_2 = \frac{A_1A_2 + A_1A_3 + A_2A_3}{A_1}$$

$$B_3 = \frac{A_1A_2 + A_1A_3 + A_2A_3}{A_2}$$

The above equations may be used either with percentages having a common kva base or with ohmic values.

To obtain the initial symmetrical short circuit kva at the fault location, the over-all percent reactance, which was deter-

TABLE 4 — AVERAGE PERCENT IMPEDANCE OF 60-CYCLE POWER TRANSFORMERS [1 & 2]

(Approximately equal to percent reactance)

Hv Class Kv	Max. LV Class Kv	Percent Impedance Limits: At Self Cooled Kva Rating — Min.	At Self Cooled Kva Rating — Max.	At Forced Cooling Kva Rating of 166-2/3% of Basic Kva — Min.	At Forced Cooling Kva Rating of 166-2/3% of Basic Kva — Max.
15	15	4.5	7	6.75	10.5
25	15	5.5	8	8.25	12
34.5	15	6	8	9	12
	25	6.5	9	9.75	13.5
46	25	6.5	9	9.75	13.5
	34.5	7	10	10.5	15
69	34.5	7	10	10.5	15
	46	8	11	12	16.5
92	34.5	7.5	10.5	11.25	15.75
	69	8.5	12.5	12.75	18.75
115	34.5	8	12	12	18
	69	9	14	13.5	21
	92	10	15.5	15	23.25

Hv Class Kv	Max. LV Class Kv	Percent Impedance Limits: At Self Cooled Kva Rating — Min.	At Self Cooled Kva Rating — Max.	At Forced Cooling Kva Rating of 166-2/3% of Basic Kva — Min.	At Forced Cooling Kva Rating of 166-2/3% of Basic Kva — Max.
138	34.5	8.5	13	12.75	19.5
	69	9.5	15	14.25	22.5
	115	10.5	17	15.75	25.5
161	46	9	14	13.5	21
	92	10.5	16	15.75	24
	138	11.5	18	17.25	27
196	46	10	15	15	22.5
	92	11.5	17	17.25	25.5
	161	12.5	19	18.75	28.5
230	46	11	16	16.5	24
	92	12.5	18	18.75	27
	161	14	20	21	30

[1] For autotransformer select value from above table as though it were a two-winding transformer and multiply this value by $\frac{KV_{HT} - KV_{LT}}{KV_{HT}}$

[2] Impedances of 25 cycle power transformers are approximately the same as the minimum values for 60 cycles.

TABLE 5 — PERCENT IMPEDANCE OF DISTRIBUTION TRANSFORMERS

(Maximum capacity 500 kva)

Primary Voltage Class	Range of Impedance in Percent
480-600	2.7 - 3.8
2,400-4,800	2.7 - 4.5
6,600-13,200	4.0 - 4.8
22,000	5.0 - 5.6
33,000	4.8 - 5.4
44,000	5.2 - 6.1
66,000	5.9 - 6.7

IMPEDANCE OF
25-CYCLE TRANSFORMERS
Distribution Transformers — Approx. 80% of 60-Cycle Values

TABLE 6 — PERCENT IMPEDANCE OF LOAD-CENTER UNIT SUBSTATION TRANSFORMERS

3-Phase Capacity in kva	Percent Impedance: Oil or Askarel	Percent Impedance: Air
100	4	4
150	4	5
200	4.5	5
300, 450, 500	5	5
600, 750	5.5	5.5
1,000, 1,200, 1,500, 2,000	5.5	6

TABLE 7—CONVERSION OF R, X, OR Z FROM OHMS TO PERCENT

$$\text{Percent} = \frac{\text{kva base}}{10\,(\text{kv})^2} \times \text{ohms} = \text{K} \times \text{ohms} \qquad \text{ohms} = \frac{\% \times 10\,(\text{kv})^2}{\text{kva base}} = \frac{\%}{\text{K}}$$

Volts	FACTOR K				Kv	FACTOR K			
	Kva Base					Kva Base			
	1,000	5,000	10,000	20,000		1,000	5,000	10,000	20,000
240	1,730	8,650	17,300	34,600	23	.189	.945	1.89	3.78
480	433	2,170	4,330	8,660	34.5	.084	.420	.840	1.68
550	330	1,650	3,300	6,600	46	.0472	.236	.472	.944
600	277	1,390	2,770	5,540	69	.0210	.105	.210	.420
2,400	17.4	87.0	173.7	347.4	92	.0118	.059	.118	.236
4,160	5.77	28.8	57.7	115.4	115	.00755	.0377	.0755	.151
4,800	4.33	21.6	43.3	86.6	138	.00524	.0262	.0524	.1048
7,200	1.93	9.65	19.25	38.5	161	.00385	.0192	.0385	.0770
12,470	.643	3.21	6.43	12.86	196	.00260	.0130	.0260	.0520
13,800	.524	2.62	5.24	10.48	230	.00189	.00945	.0189	.0378

mined as described in the preceding paragraphs, is used in the following equation:

$$\text{Initial symm. short circuit kva} = \frac{\text{Base kva} \times 100}{\%\ \text{reactance}}$$

The initial value thus obtained is then applied as outlined under "General Calculating Procedure."

When short circuit kva into faults at various points in a system are to be calculated the steps described above must be repeated for each fault location.

In the case of a large or intricate power system, calculation of short circuit values by the methods outlined in the foregoing would be very laborious if not impossible. In such cases the values should be determined by means of a network calculator.

Calculations with neutral grounded

In three-phase systems of the "grounded neutral" type "phase to ground" faults may occur in addition to "phase to phase" faults. For this reason calculation of the "phase to ground" fault value should be made in addition to calculation of the three-phase fault value as previously explained. Circuit breaker selection is then based on the larger of the two values.

Of the two the "phase to ground" fault may be the most severe and may occur more frequently. Some systems have solidly grounded neutrals and others are grounded through reactors or resistors. Where grounding is through impedance the reactor or resistor is usually of such value as to limit "phase to ground" faults to magnitudes not exceeding those of "phase to phase" faults.

For application of circuit breakers on a solidly grounded system, calculations should be made to determine the equivalent short circuit kva based on short circuit current in the faulted phase. These calculations are made in the same manner as those outlined in previous sections for three-phase faults but with different reactance values applied to generators (other rotating machines do not ordinarily have grounded neutrals), transformers, and lines. These reactances are positive sequence reactance X_1 and zero sequence reactance X_0. For X_1 use the subtransient reactance values which were used in previous sections. Average values for X_0 may be found in Tables 2 and 3. For three phase current limiting reactors use the same reactances as were used in previous sections.

The reactance X which is used in calculating equivalent three-phase short circuit kva corresponding to a "phase to ground" fault on a generator with a solidly grounded neutral is found by the following equation:

$$X = \frac{2X_1 + X_0}{3}$$

and:

$$\text{Equiv. } 3\,\phi \text{ short circuit kva} = \frac{300 \times \text{rated kva}}{2X_1 + X_0} \text{ or } \frac{100 \times \text{rated kva}}{X}$$

If a group of generators is connected in parallel and the neutrals of some are solidly grounded while others are ungrounded the reactance X which is used in calculating the equivalent three-phase short circuit kva of the group for a "phase to ground" fault is found by the following equation:

$$X = \frac{2\,[\text{combined } X_1 \text{ of group}] + [\text{combined } X_0 \text{ of grounded generators}]}{3}$$

In the above equation X_1 and X_0 must be in percent on a common kva base.

Limitation of the ground fault current of a group of generators in parallel to a value not exceeding the three phase fault current of the group may be attained by leaving some generators ungrounded while others are grounded but such an expedient may impose excessive ground fault currents on the grounded generators. For this reason limitation of ground fault current is preferably accomplished by inserting reactance or resistance between generator neutrals and ground.

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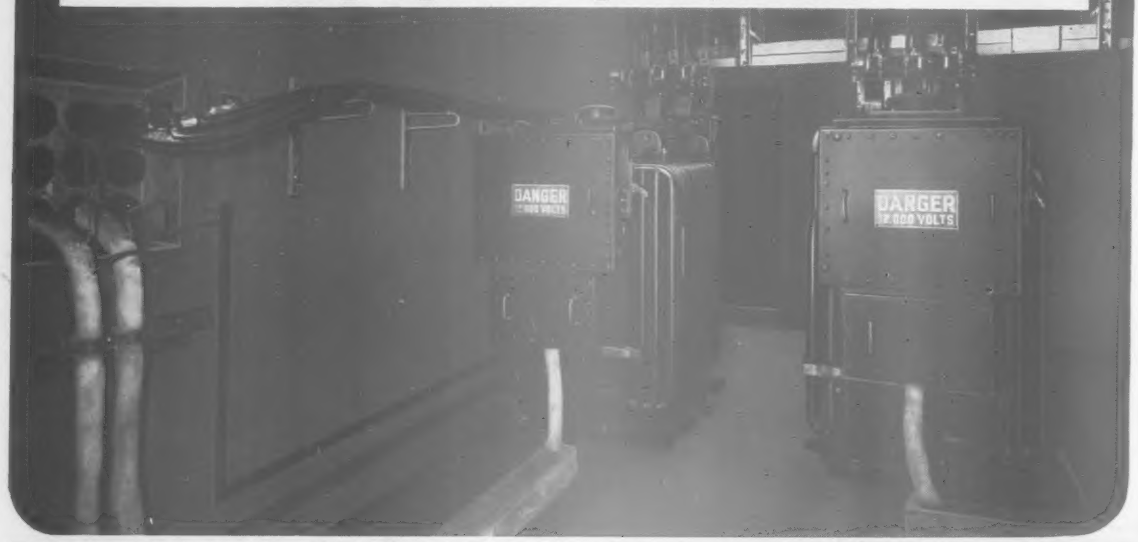

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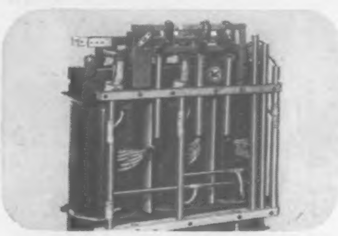

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